THE UNIVERSITY OF ALBERTA

AN INTERPRETATION OF SOME GRAVITY MEASUREMENTS IN THE CANADIAN CORDILLERA

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF PHYSICS

by

E. R. Kanasewich

Edmonton, Alberta

September, 1960

ABSTRACT

The thickness of the Athabaska glacier has been obtained along eight transverse profiles by an investigation of gravity anomalies. Three dimensional computations with a low speed digital computer were made in this study to acquire more precise results than previously obtained. The depth of the glacier varied from 1070 feet on a line below the lower ice fall to 160 feet near the terminus. The accuracy of the results are discussed and compared with independent data from boreholes and a seismic program. The cross section of the valley of the glacier was found to approximate a parabola on several lines. From a knowledge of the depth, shape and surface slope of the glacier, the average shear stress exerted by the bed on the ice was found to be 1.0 bars.

Gravity studies along the Rocky Mountain Trench south of Cranbrook, British Columbia, revealed the presence of three deep basins filled with unconsolidated material. The basins range in depth from 1400 to 3500 feet (-17% to +25%). Combined gravity and geologic data indicate that the Trench south of Fort Steele is

due fundamentally to block faulting with the amplitude of faulting increasing towards the International Boundary. A linear gravity minimum is associated with the Moyie Lenia fault southwest of Cranbrook. This trend is really composed of two high anomalies, one on each side of the fault, which are caused by dense sills of basaltic material intruding the Aldridge formation. The upthrown block, on the northwest side, brings the Aldridge formation and sills to the surface. From geologic evidence the down thrown side has a vertical displacement of about 15,000 feet. To satisfy the gravity data the total thickness of the sills and intervening quartzites should increase from 2000 to 5000 feet as one passes over the fault towards the southeast. Gravity calculations were made treating the break as a steeply dipping overthrust and as a normal fault. Of the two interpretations presented the normal fault solution fits the observed gravity data better. Important faults such as the Dibble Creek and Boulder Creek faults, which appear in the Rocky Mountains, extend at least four miles into the trench.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

In the summer of 1959 the University of Alberta and the University of British Columbia undertook an expedition to the Athabaska Glacier to study particular problems in the geophysics of glaciers. The program was sponsored by the National Research Council of Canada and was under the direct supervision of Professor J. A. Jacobs and Professor G. D. Garland. The major factor determining the selection of the glacier to be studied was ease of access. The Athabaska Glacier was an obvious choice as it is a smooth valley glacier with a well defined terminus which is only one-half mile from a major paved route. It is also 65 miles from the town of Jasper on the main railroad line between Edmonton and Vancouver. Heavy equipment was transported two and one-half miles from the toe of the glacier to the 7300 foot level by Snow-mobiles operated by Mr. Wm. Ruddy.

The major part of the program was designed to determine the mechanics of glacier flow. In this connection 80 stakes were set out for a study of surface movement and ablation by Stan Paterson of the University of British Columbia. The variation of velocity with depth

was to be determined by long term study of inclinometer measurements in cased boreholes following a method pioneered by Gerrard, Perutz and Roch (1952). John Stacey was in charge of designing the hotpoints, the drilling procedure, and general camp routine.

The thickness of the ice along a longitudinal traverse was determined by reflection seismograph methods with a set of Houston Technical Laboratories High Resolution instruments. One borehole penetrated the ice column to bedrock and provided valuable velocity control for this seismic study. Professor J. C. Savage was in charge of the seismic operations. The thickness of the ice and the shape of the bedrock along transverse profiles was to be obtained by a gravity investigation using the Worden Gravity Meter. The gravity study was planned to provide a detailed description of the thickness of the glacier so that the movement studies could be properly evaluated and the average shear stress on the bedrock calculated. It would then form a valuable adjunct to the seismic program which was much more expensive to carry out and, therefore, limited in scope. In addition, the gravity data checked areas with poor seismic reflections and depth points determined from events suspected of being multiple in origin.

In addition to the above studies, Professor G. D. Garland made temperature measurements in uncased boreholes to determine the thermal regime of the glacier. Independent investigations were carried out by other parties on the same glacier during the 1959 season. These included a detailed aerial photographic and topographic survey by the Water Resources Branch of the Department of Northern Affairs and National Resources. This survey established a series of valuable benchmarks around the perimeter of the Athabaska Glacier. Various experiments to determine the thickness and electrical properties of an ice sheet by electrical and electromagnetic methods were conducted by A. Don Watt and Gene Maxwell of the United States Bureau of Standards and by Henri Vetter from the University of Alberta.

The gravity investigation of the glacier forms the first topic of this thesis. The second part of the thesis is a gravity investigation of the Rocky Mountain Trench between Cranbrook, British Columbia, and the International Boundary. The two topics are related because the major anomalies in both areas are prominent negative minima. At the Athabaska Glacier, the anomaly is due to low density ice filling a mountain valley while in the Trench, the anomalies are due to depressions

in the bedrock filled with low density unconsolidated material. In both cases one face of the body producing the minimum, that is the surface, is completely determined. The interpretation of the gravity data is, therefore, similar in principle.

PART I

AN INTERPRETATION OF SOME GRAVITY MEASUREMENTS ON THE ATHABASKA GLACIER, ALBERTA

2. PHYSICAL DESCRIPTION OF THE AREA

2.1 The Columbia Icefield

The Athabaska Glacier is the second largest ice stream issuing from the Columbia Icefield, an ice cap straddling the Continental Divide which marks the boundary between the provinces of Alberta and British Columbia. The Columbia Icefield covers an area of 110 square miles and is contained by a series of peaks, nine of which are over 11,000 feet above sea level. These include Mt. Columbia (12,294'), and the North Twin (12,085'), respectively the second and third highest peaks in the Rocky Mountains. The area of accumulation, with an average elevation of nearly 10,000 feet and a maximum of 11,340 feet on the Snow Dome, has an abundance of snow precipitation in the winter and throughout the year. The elevation is sufficiently large for the temperature to be low so that much of the fallen snow is conserved and transformed into ice. (See Figure 1 and Plate I.)

The Columbia Icefield and Athabaska Glacier were discovered by Professor J. N. Collie, H. E. M. Stutfield and Hermann Wooley in 1897. In 1919 Dr. A. O. Wheeler

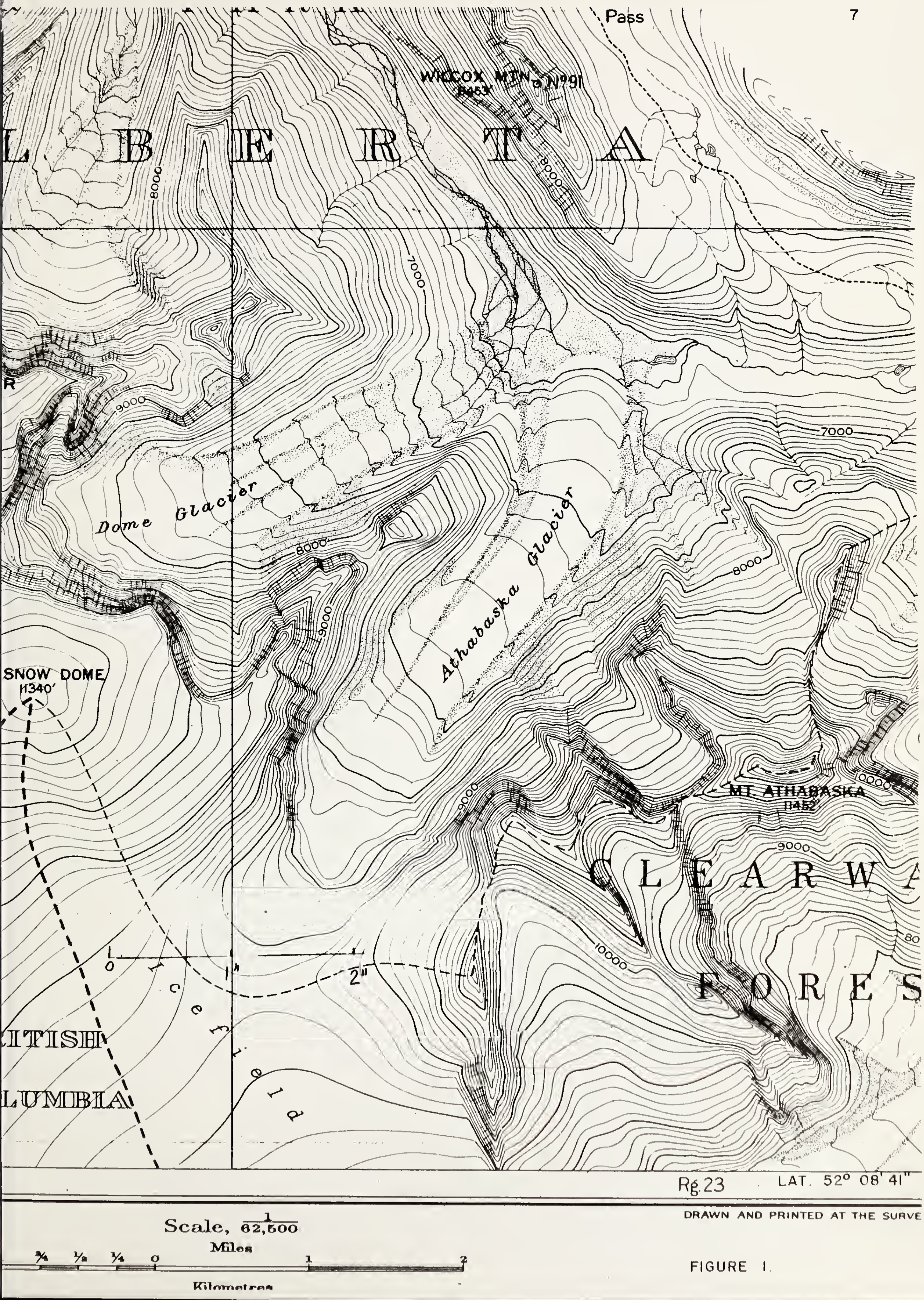

Pass
WILCOX MTN
L B E R T A
8000
7000
9000
Dome Glacier
Athabaska Glacier
SNOW DOME
11340'
MT. ATHABASKA
11452'
10000
C L E A R W A
F O R E S
Icefield
ITISH
LUMBIA
0
1"
2"
Rg.23
LAT. 52° 08' 41"
DRAWN AND PRINTED AT THE SURVE
Scale, 1/62,500
Miles
Kilometres

FIGURE I.

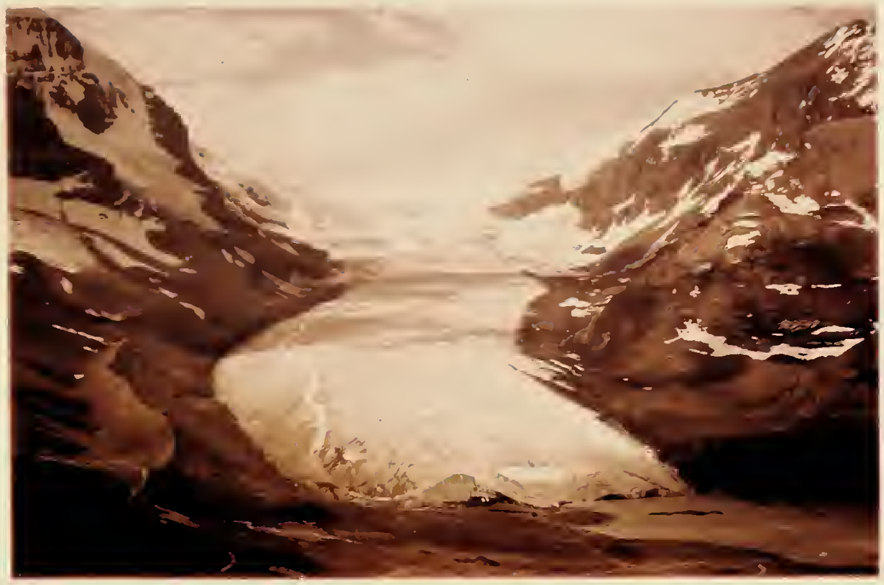


PLATE I. Two photographs of the Athabaska Glacier from Mount Wilcox. Mount Athabaska (11,452') is on the left side. The lower photograph shows details of the three steps which lead to the Columbia Icefield. Snow Dome (11,340') is out of sight on the upper right hand side.

and R. W. Cautley led parties which surveyed and photographed the region of the Continental Divide for the Canadian Government. The topographic maps produced by the Interprovincial Boundary Commission are on a scale of 1:62,500 and have a contour interval of 100 feet. (See Figure 1.) These maps have proven invaluable in computing the topographic correction for this gravity survey.

2.2 The Athabaska Glacier

The glacier issues from the Columbia Icefields at an elevation of about 9000 feet and flows 4 miles to the northeast to a well defined terminus at 6320 feet above sea level. The upper half of the glacier descends in three sharp drops to form two prominent steps. The lower half is 2-1/4 miles long and descends smoothly from an elevation of 7500 feet with a dip of 3-1/2° at station L 10, decreasing to 2-1/2° at L 22 and gradually increasing to 10° at L 36 and about 30° at the terminus. The majority of the observations were made on this smooth lower half. The fresh winter snow retreats from the lower part of the glacier during the early part of July and towards the end of the month the ice is exposed all the way to the second step. The firn line is on the upper part of the ice drop from the icefield. The glacier

is the source of the Sunwapta river which joins the Athabaska, Slave and Mackenzie rivers to flow 2200 miles into the Arctic Ocean.

European records of glacier retreats and advances are fairly complete as far back as 1850 when a pronounced advance was recorded in the Alps, Iceland, and Greenland. A recession was recorded between 1860 and 1870 and a minor advance between 1875 and 1890. Since the 1890's there has been a slow general recession in Europe and America. Regular observations on the terminus of the Athabaska glacier were begun in 1945 by the Water Resources Branch, Department of Northern Affairs and National Resources. The amount of recession between 1945 and 1956 amounted to 468 feet, which is an annual recession of 58.5 feet. During the same period a series of plaques on the snout of the glacier advanced at a mean annual rate of 51 feet. (Collier, 1957).

Additional data can be obtained from the 1919 Boundary survey maps and photographs made by Cautley and Wheeler. These indicate a recession of 2700 ± 200 feet in 40 years or an annual mean recession of 68 ± 5 feet.

2.3 Geology of the Area

The Athabaska glacier has formed a terminal moraine nearly 3/4 mile long during its retreat. On either side

it is bounded by high lateral moraine made up of loose, fairly fresh looking limestone debris. To the southeast the lateral moraine is 70 feet above the ice surface and extends from the E line to the terminus. It is not known if ice underlies this material. The wide northwest embankment is covered with loose and unstable slabs of limestone rock and is known to contain glacier ice under the material. The ice outcrops in several places, notably between lines H, F and G. The known exposures are 30 to 70 feet above the level of the central clean ice and is protected from ablation by the mantle of rock. An alluvial plain extends along the Sunwapta valley for several miles.

No detailed geologic work has been published for this area. J. A. Allan (1938) made a regional survey of the immediate area and R. D. Hughes (1953) has made a detailed study of the Sunwapta Peak area some 10 miles to the north. J. L. Severson (1950) studied the Devonian stratigraphy in the Sunwapta Pass area. A useful map can be found in the Guidebook for the Fifth Annual Field Conference (1955) published by the Alberta Society of Petroleum Geologists. Rocks in this area range in age from Cambrian to Mississippian. In only a few places is the folding extreme and rarely does faulting complicate the picture.

The cliff of shaly limestone on the west side of Sunwapta River below Mt. Kitchener has been identified as Middle Cambrian by Allan. The overlying strata of buff calcareous shales may be Upper Cambrian. About ten miles to the southwest near the Columbia glacier P. E. Raymond (1928) described two Middle Cambrian trilobites. The strata on the east side of the road above the Chalet are probably Middle Cambrian shales.

The Athabaska glacier flows across the axis of a long trending anticline. With minor offsets this anticline runs to the east of Mt. Edith Cavell, 45 miles to the northwest, through the glacier, and continues south of Mt. Sarbach 30 miles to the southeast. A thick succession of Lower Cambrian quartzites are exposed at Edith Cavell, while Middle and Upper Cambrian is seen at Mt. Kitchener; Ordovician at Mt. Erasmus and Devonian at Mt. Sarbach. It is evident that the axial trend is N 40° W to N 50° W, parallel to that of the Rocky Mountain front in this area and that the anticline plunges to the southeast. The anticlinal axis crosses the glacier at Line B just below the first step and the limbs dip away from the axis at 10° to 15°.

The Castle Mountain Syncline passes through Nigel Peak exposing Banff shale of Mississippian age. The

structure under the Sunwapta River has not been determined but Allan mentions the possibility of a fault at the west base of Wilcox peak. This may tie in with the small thrust fault placed by Hughes where Tangle Creek runs into the Sunwapta River. (See Hughes 'Section GG'.)

3. THE GRAVITY MEASUREMENTS AND THEIR REDUCTION

3.1 The Field Work

The observation on lines A to F were made with the University of British Columbia's Worden Meter No. 35. According to the manufacturer this meter has a dial constant of 0.41874 milligals per scale division. Later in the season the University of Alberta's Worden gravity meter No. XP 0 arrived from factory servicing and observations were made with it on Lines B to H inclusive. The dial constant is 0.2607 milligals per scale division as determined by Dr. G. D. Garland. There are, therefore, two independent readings on 85 of the 127 stations occupied. Wherever possible readings with meter XP 0 were used in the calculations as the dial constant is more accurately determined, the meter is more sensitive, and it has a lower drift rate. Readings were taken over a sufficiently wide range to see that the calibration of the two meters agreed to two significant figures.

A base station was set up at C 1 behind the campsite. The location was on morainal material about a hundred feet from bedrock and measurements indicated that it was not significantly affected by ablation or horizontal movement of the ice. The horizontal velocity amounted to 1 foot per month at this station. The instrument and tripod must be accurately leveled before a reading can be taken. Maintaining a level base on the glacier is almost impossible unless the metal tripod legs are insulated from the ice. Following recommendations of members of Operation Hazen to Ellesmere Island, plasticene was tried and found to provide excellent insulation.

The Worden gravimeter is an astatic instrument built of fused quartz and housed in a partial vacuum. It measures small variations in the vertical component of gravitational attraction by balancing the torque produced by a mass on the end of a horizontal arm with the restoring force of a spring. The astatic element consists of a spring which acts in the same direction as the force of gravity and nearly cancels the elastic restoring force. The unit of measurement is 0.001 $cm./sec.^2$ and is termed the milligal.

The primary base station was on the Banff-Jasper highway. The absolute value of the acceleration of gravity

was obtained from measurements by Garland and Tanner (1957) at their station No. 459 (Gatehouse). From this point the new base station at C 1 was set up by a system of looping. That is, observations were made at station 459, next at a new station which we can call A and then again at 459. Proceeding to a new loop observations were made at stations A, B and A. All closed loops which established bases were completed in less than one hour and the instrumental drift was determined and corrected using a linear drift rate. From the behavior of the drift curves between sequential loops it is estimated that the base at C 1 is correct within 0.1 milligal.

In carrying out the survey over the glacier the instrument was back-packed over rough glacier ice and was subjected to shocks which made the drift rate more erratic. Ties were made at base stations at least once every two hours. From a study of the drift curves and a comparison of the values obtained with the second meter it appears that all readings are within 0.2 milligals except for 6 stations which do not agree by 0.3 to 0.5 milligals. This agreement is quite good considering that measurements with the two meters were made two to three weeks apart and it is not certain that

ablation which varied between 0 and 3 feet has been exactly corrected for. Since depth determinations were made on individual traverse lines independently of observations made elsewhere, the accuracy of each line should be considered separately. On this basis errors between stations all on one line do not exceed 0.1 milligals.

3.2 Surveying

All the stations were surveyed by plane table and alidade and the ties around closed loops were within one foot. Many extra points were surveyed on the mountain slopes adjacent to the glacier so that accurate terrain corrections could be made. The movement stakes were surveyed independently by S. Paterson with a Wild T 2 (57767) Theodolite and these measurements have recently been reduced. The results are in agreement within one foot. All the surveying is based on the Water Resources Branch Bench Mark No. 1 which has coordinate:

Latitude: 52° 13' 12"
Longitude: 117° 13' 30"
Elevation: 6468.04 feet

Additional horizontal control was obtained from Bench Mark 17 near the camp. Its latitude is 52° 11', 13"; the longitude is 117° 15' 08".

Attempts at using a barometer as an altimeter were not successful as the temperature and pressure varied from the sides to the middle of the glacier. The measurements were generally accurate within 10 feet so the barometer was used to fill in topographic details within 250 feet of a station. Routine readings were made in camp which has an altitude of 7340 feet. The altimeter reading at camp varied between 7078 and 7640 with the reading occasionally rising by 400 feet within a few hours when a storm was impending.

To estimate the amount of horizontal movement down the glacier two markers were set up on bedrock on either side on the glacier. The Wild T-2 Theodolite was aligned with these markers and the holes for the stakes on Line C were drilled within 0.1 feet of this line. Forty-five days later the instrument was reset in its original position and the original line marked on the glacier opposite each stake. The down-dip movement of the stakes was then measured simply with a tape. The results are shown in Table I, when reduced to a 30 day month.

The thickness of the ice along the flanks was determined from this gravity survey while the maximum depths are from a borehole 200 feet from the line. There is a qualitative relationship between the depth and the

TABLE I. Surface Movement Studies on C Line

Stake Number	Velocity (feet per month)	Vertical Thickness of Ice in Feet
C 1	1.0 ± 0.1	140 ± 20%
C 2	4.9 0.1	330 20%
C 3	10.0 0.1	550 20%
C 4	11.6 0.1	700 20%
C 5	12.6 0.1	830 ± 10%
C 6	13.1 0.1	940 10%
C 7	13.7 0.1	990 10%
C 8	14.0 0.1	1020 10%
C 9	14.2 0.1	1020 10%
C 10	14.0 0.1	980 10%
C 11	14.3 0.1	910 10%
C 12	13.1 ± 1.0	740 ± 20%
C 13	11.7 ± 0.1	640 20%
C 14	5.7 0.1	420 20%
C 15	0 0.1	160 20%

surface velocity on this line. A major problem on many glaciers which have an extensive lateral moraine is to determine the zero ice thickness line. It is evident that velocity measurements of this type can locate this line within 100 feet. Difficulties may be encountered in the lower portions of the glacier where stagnant ice may be present. Although the gravity measurements were made on a moving surface, this study indicates that the movement was not enough to warrant a latitude correction.

The rate of ablation was determined from measurements on the movement stakes which were drilled into the ice a depth of 7 feet. The ablation during July varied from 0 to 5 feet per month, the amount depending on the location of the stake. Since the surveying and the gravity measurements were made one to three weeks apart, a correction to the altitude was necessary.

3.3 The Reduction of the Gravity Measurements

The principal facts for the gravity stations are set out in Table II. This table gives the station, line number, longitude, latitude, elevation, observed gravity and the various types of anomaly. It is necessary to correct for variations of gravity with latitude, elevation of the station above the reference surface or geoid at sea level and the attraction of the surrounding

topography. The remaining figure is termed the Bouguer anomaly and is related to the anomalous mass variations within the earth.

The variation of gravity with latitude is given by the International Gravity Formula (1930).

$$\gamma = 978.0490(1 + 0.0052884 \sin^2 \phi - 0.0000059 \sin^2 2\phi) \text{ cm/sec}^2$$

$$\phi = \text{latitude of station}$$

The variations amount to 0.024 milligals per second of latitude (101.6 feet) at the glacier.

The free air correction amounts to - .094057 H milligals where H is the altitude in feet above sea level. This corrects for the decrease in gravity with height above sea level. The Bouguer correction amounts to 0.034057 H milligals if the density of the material between the surface and sea level is 2.67 grams per cubic centimetre. This corrects for the attraction of an infinite horizontal slab of material between the geoid and the earth's surface. A terrain correction, T, is then made to account for the topographic variation of the surface above and below the level of the station. The complete expression for the Bouguer anomaly is:

$$g = g_{observed} - \gamma + 0.094057\ H - 0.034057\ H + T$$

The expression is termed a simple Bouguer anomaly if no terrain correction is made. Figure III is a contour map of the Bouguer anomalies. (See Appendix.)

To correct for the topography, the area surrounding a station is divided into cylindrical zones bounded by radii r_1 and r_2. Each annular zone is subdivided into N sectors. The attraction of each sector is given by the formula: (Heiland, p. 149).

$$T = k \frac{360}{N} \delta \left\{ r_2 - r_1 + \sqrt{r_1^2 + h^2} - \sqrt{r_2^2 + h^2} \right\}$$

where h is the average height of the sector above or below the station, δ is the density and k is the gravitational constant.

Hayford's values for the radii were used and corrections were made to all stations for his zones A to J inclusive. This corrected for the topographic effect of the mountains and valleys to a distance of 7.7 miles. The effect of the terrain beyond this distance is nearly the same over the entire glacier and does not affect the accuracy of the relative gravity anomalies. Bullard (1935) has published a table evaluating the above formula for different values of r and h. This table is not accurate enough for modern gravity surveys and a new table was computed for use here.

Estimating the heights in each of the 96 sectors surrounding a station involved the greatest amount of labour. Care had to be taken to distinguish between

sectors containing ice which has a density of 0.90 and sectors containing rock with a density of 2.67. The reduction of terrain corrections for 125 stations required about one month to complete. The corrections for Hayford zones B to J are set out in Table III. The terrain corrections were very large because of the proximity of Mt. Athabaska (11,452'), Snow Dome (11,340'), Mt. Kitchener (11,500') and the Sunwapta valley (6300'). The maximum correction was 14.9 milligals and the minimum was 6.31 milligals.

3.4 Density of the Ice and the Rock Samples

The density of fresh fallen snow is about 0.06 to 0.16 gms. per cc. and by a complicated process of melting and refreezing it forms nevé with a density of 0.45. Since the glacier was entirely free of snow or nevé when the gravity measurements were made, no correction was necessary for this light material.

The theoretical density of pure ice can be calculated from a knowledge of the lattice constants and is 0.9168 gm. per cc. at 0° C. As the depth of burial is increased the air bubbles in the nevé are expelled; however, some are trapped and gaps are formed between the ice crystals so that the theoretical value is never realized. Mercantour (1950) has studied the subject and concludes that a good figure to use for glacier ice is 0.90 gm. per cc.

Rock samples were collected from the area on either side of the glacier and the results of the density measurements are given in Table V. The samples are listed in approximate stratigraphic order with the youngest rocks at the top of the Table. The samples are probably all of Cambrian age.

The mean density by rock type is as follows:

TABLE IV. Mean Density of the Rock Types

Number of Samples	Rock Type	Mean Density gm/cc.
15	Limestone and Dolomite	2.69
9	Shale	2.79
4	Sandstone and Quartzite	2.61

It is difficult to decide if this suite of rocks is representative of the area in which terrain corrections were made. Limestone is the predominant rock which outcrops in this area and it appears that the density of 2.67 gm. per cc. used in the corrections is very nearly the correct one.

It is expected that Lower Cambrian quartzites appear at some level beneath the glacier surface. Inconclusive evidence to this effect was obtained from a seismic refraction line shot along the glacier. It was

TABLE V. Densities of Rock Samples

Rock Type	Locality	Density gm./cc.
CAMBRIAN SYSTEM		
Limestone, black, with calcite veins, cliff forming	Above B 10	2.69 2.71
Limestone, black, fine grained	Above BM 17	2.68
Shale, dark grey, calcareous	Above BM 17	2.82 2.83
Limestone, black, fine grained Basal unit on south side	Above BM 17 Above BM 17	2.71 2.72
Limestone, light grey, massive, hard	Opposite B 10	2.69
Dolomite, dark green, hard, well bedded about 300' thick	Above M 23	2.63 2.67
Limestone, light grey, and cherty dolomite, weathers yellow	Opposite M 14	2.82 2.83
Limestone, black, massive, with calcite veins. About 50 feet thick	Above D L on north side	2.73 2.69
Limestone, dark grey, shaly	Above D L on north side	2.60 2.61
Shale, grey, well bedded	Above D L on north side	2.72
Limestone, black, poorly preserved trilobite fragments.	Above D L on north side	2.63
Sandstone, quartzite, well cemented, light yellowish grey	Above D L on north side	2.58 2.63
Shale, dark grey	Above D L on north side	2.76 2.79 2.81 2.77
Shale, dark grey	Above D L on north side	2.83
Quartzite, pinkish white Basal unit on south side	Above D L on north side	2.66 2.58
	MEAN DENSITY	2.71

hoped that arrivals from a high velocity layer such as a bed of Middle Cambrian limestone would be detected by the refraction program. Tentative study of the time-distance plot indicates that first arrivals travelled with a velocity of 12,200'/s through the ice while the secondary arrivals indicate velocities no higher than 14,000 feet per second. This is a velocity that would be expected from a layer of sandstone but is far too low for a bed of consolidated limestone. The mean density of the sandstones is lower than was expected and there may have been some leaching which increased the porosity. However, the density is only 2% lower than the value of 2.67 which was used in calculating the thickness of the ice column. The density difference (between rock and ice) used in all computation was 1.77 gm. per cc. and this figure appears to be correct within 2%.

3.5 Accuracy of the Data

The relative field measurements on each line are accurate to within 0.1 milligals. The elevations are known to a precision of $\pm$ 1 foot so that the combined free air and Bouguer corrections are accurate to $\pm$ 0.06 milligals. The principal error and the one that is most difficult to evaluate is that due to the terrain

corrections. The uncertainty in the density contributes an error of about 2%. This produces an error of 0.1 milligals between a station in the middle and a station at the sides of the glacier. For each station there are 96 sectors each of which is subject to an error of about 0.01 milligals. These reading errors are in the nature of a "random walk". In the measured quantity T there are 96 causes of error, each of which will add the amount 0.01 or -0.01 with equal probability. The probability of an error of $\pm$ 0.04 is only 0.2 while the probability of an error as large as $\pm$ 0.1 milligals is 0.004.

In the preceding discussion it has been tacitly assumed that the topographic maps are perfect. In some of the zones a determinate error may be introduced due to a systematic distortion of the contours. A large scale map on the scale of 1:4800 was constructed and contoured in the field. Zones B and C which cover an area with a radius of 755 feet were entirely corrected using this map and it is unlikely that any significant error was introduced here. Zones F to J which cover an annular area 1.4 to 7.7 miles from a station were also corrected on maps of adequate scale and accuracy. The 1919 topographic maps on a scale of 1:62,500 are not

adequate for correcting zones D, E and F. The magnitude of the error can only be roughly determined from plausible changes in the shape of the contours. It is estimated that the error is no more than $\pm$ 0.2 milligals. The terrain corrections are, therefore, thought to have a precision of at least $\pm$ 0.4 milligals and the precision of the Bouguer anomaly is $\pm$ 0.5 milligals.

4. THE INTERPRETATION OF GRAVITY ANOMALIES OVER A GLACIER

4.1 Introduction

The interpretation of gravity anomalies involves an evaluation of the mass distribution causing the anomaly. A unique interpretation cannot be found as this is a problem in potential theory, and one can rearrange the subsurface mass distribution in an infinite number of ways to reproduce the same gravitational field. In the present problem there is additional information which places restriction on the interpretations possible. The density difference producing the anomaly is known within 2%. If the shape of the bedrock profile were known, the central depth to bedrock would be the only unknown variable and it could be determined exactly from a knowledge of the gravitational field. Sometimes the depth of a glacier will be known from a borehole or from seismic work. In this case the shape of the bedrock

profile can be determined approximately. The detection of small sinusoidal variations on the bedrock would be limited by the accuracy of the gravity data.

Determining the thickness of a glacier with gravity data was first attempted in 1955 on the Austerdalsbre, a Norwegian glacier, by C. Bull and J. R. Hardy. No topographic maps were available so conventional terrain corrections could not be made. An estimate of the effect was made by three traverses at the foot of the glacier. The thickness was calculated by assuming that the sheet of ice extended to infinity in a horizontal direction. Essentially this is a Bouguer correction which is useful in mapping an ice-sheet as shown by C. A. Littlewood on Baffin Island in 1952. The method can seldom be applied to a glacier as it is a three dimensional, or at best, a two dimensional body. The Austerdalsbre could be regarded as an ice sheet of infinite extent because it was less than 100 meters thick and about 1000 meters wide. The principal errors arise from the method of making terrain corrections. The authors claim that these are correct within 1 to 2 milligals in the center. Errors in the ice thickness are given as 20% on the lower two profiles and 40% on the upper two.

Thiel, LaChapelle and Behrendt made gravity measurements on the Lemon Creek Glacier, Alaska in 1956. No

topographic maps were available and terrain corrections were made approximately with a two dimensional model of the mountain, the model extending to infinity in the third direction. A correction was made for the regional trend by comparing the Bouguer anomaly of the end stations. As at the Austerdalsbre, a first approximation was made by applying the infinite slab Bouguer correction. However, in this case, a second approximation was made by a line integral method of calculating the gravity of any desired cross section (Hubert, 1948). The Lemon Creek glacier proved to be a little over 200 meters deep but the authors do not give an estimate of the accuracy.

Jacobs, Grant and Russell made gravity measurements on the Salmon Glacier, B.C. This is a deep glacier with a borehole reaching a depth of 725 meters. The interpretative technique was a two dimensional variant of the one used by Thiel, et al. The accuracy of the data is discussed fully and the thickness is believed to be correct within -10% and +25%. Most important was a comparison with seismic and borehole data on one line. The agreement between these data was within 10%.

4.2 Theory of Gravity Calculations

The potential at the origin, P, due to a mass of

density, δ , distributed evenly throughout a volume, τ , not occupying the origin is:

$$U = k\delta \iiint_{\tau} \frac{dx\ dy\ dz}{\sqrt{x^2 + y^2 + z^2}} \tag{1}$$

A left handed cartesian coördinate system is employed, with the z axis vertically downward. The gravitational constant is denoted by the symbol "k". If we let $r^2 = x^2 + y^2$ and change to cylindrical coördinates (r, ψ, z), (1) becomes:

$$U = k\delta \iiint_{0}^{r} \frac{d\psi\ dz\ r\ dr}{\sqrt{r^2 + z^2}} \tag{2}$$

$$U = k\delta \iint \left\{ \sqrt{r^2 + z^2} - z \right\} d\psi\ dz$$

The gravity anomaly due to a pie-shaped prism of thickness dz and radius r is:

$$\Delta g = -\frac{\partial U}{\partial Z} = k\delta \iint \left\{ 1 - \frac{z}{\sqrt{r^2 + z^2}} \right\} d\psi\ dz$$

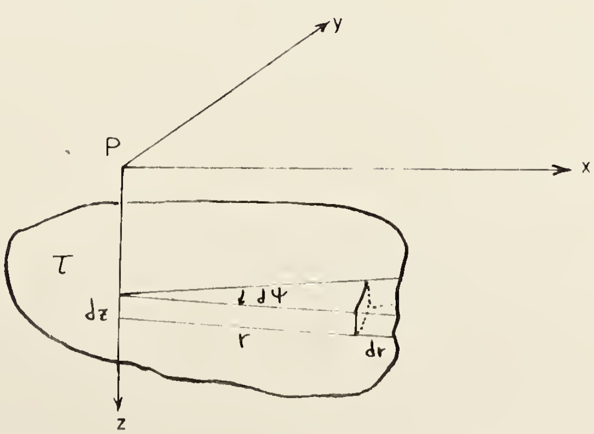


Figure 14

The gravity anomaly due to a lamina of infinitesmal thickness dz is:

$$\Delta g = V\, dz \tag{3}$$

where

$$V = k\delta \left\{ \oint d\psi - \oint \frac{z}{\sqrt{r^2 + z^2}}\, d\psi \right\} \tag{4}$$

If the radius of the lamina becomes very large the second integral approaches zero. Then,

$$\Delta g = 2\pi k\delta\, dz \tag{5}$$

which is the Bouguer correction formula for an infinite bed of thickness dz. Formulas (3) and (4) were programmed for the Royal McBee LGP-30 digital computer to obtain the gravitational attraction of the glacier at any station following the method developed by Talwani and Ewing (1960). These formulas are also the analytic basis of a mechanical integrator for the computation of gravity anomalies (Siegert, 1942).

Consider next the attraction due to a line element extending to plus and minus infinity in the y direction. From (1)

$$\Delta g = -\frac{\partial U}{\partial Z} = k\delta \int_{\infty}^{\infty} \frac{z}{(x^2 + y^2 + z^2)^{3/2}}\, dy \tag{6}$$

Let $r^2 = x^2 + z^2$, $y = \sqrt{x^2 + z^2}\tan\theta$;

$$dy = \sqrt{x^2 + z^2}\ \sec^2\theta\ d\theta$$

$$\Delta g = \frac{2k\delta z}{x^2 + z^2}\int_0^{\pi/2}\cos\theta\ d\theta \qquad (7)$$

$$= 2k\delta z/(x^2 + z^2)$$

From this formula it is easy to calculate the effect of a two dimensional body such as a rectangle (Heiland, p. 150). We can then build up a two dimensional model of a glacier. The gravitational attraction of the shaded rectangle is given by:

$$\Delta g_p = 2k\delta\int_{x=0}^{b}\int_{z=d}^{D}\frac{z\ dx'\ dz}{z^2 + (x-x')^2}$$

$$= 2k\delta\left[x\log\sqrt{\frac{D^2+x^2}{d^2+x^2}} - (x-b)\log\sqrt{\frac{D^2+(x-b)^2}{d^2+(x-b)^2}}\right.$$

$$\left. + D\left(\tan^{-1}\frac{x}{D} - \tan^{-1}\frac{x-b}{D}\right) - d\left(\tan^{-1}\frac{x}{d} - \tan^{-1}\frac{x-b}{d}\right)\right] \qquad (8)$$

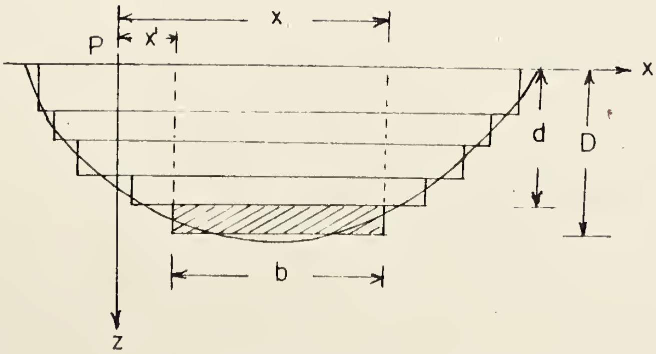


Figure 15

If (7) is converted to polar coördinates with

$$\sin \phi = \frac{z}{r} = \frac{z}{\sqrt{x^2 + z^2}}$$

$$\Delta g = 2k\delta \int_{\phi_n}^{\phi_{n+1}} \int_{r_n}^{r_{n+1}} \frac{\sin \phi}{r} \, r \, dr \, d\phi \qquad (9)$$

$$= 2k\delta (r_{n+1} - r_n)(\cos \phi_{n+1} - \cos \phi_n)$$

In graphical interpretation this formula is used to construct a graticule chart. The gravity anomaly is obtained by superimposing the chart on a cross section of the glacier with the origin at the gravity station and counting the sectors within the outline of the glacier. Nettleton (p. 117) provides a useful formula and table to give an "end correction" for reducing the gravity effect of a two dimensional body to a body of finite length.

4.3 A Two Dimensional Model of the Glacier

The process of finding the depth and shape of a glacier is essentially a trial and error process. Formula (8) for a two dimensional model with rectangular cross section can be adapted as shown in the diagram below the formula to yield the gravity anomaly of any arbitrary shape to any desired accuracy by choosing (D - d) small enough. Alternately a graticule chart can be made using formula (9) with $(r_{n+1} - r_n) = 1$ unit and $(\cos \phi_{n+1} - \cos \phi_n) = 0.05$. The gravity anomaly of

any two dimensional body of arbitrary cross section can be found in 3 to 5 minutes per station. This is considerably faster than computation with formula (8).

Geomorphologists have described glacier valleys as being U-shaped or parabolic. H. Svensson (1959) has demonstrated that the glacial valley Lapporten in northern Sweden can be described by an equation of the form

$$y = Ax^b$$

in which b is very nearly 2. It was, therefore, decided that a good first approximation to the shape of the bedrock beneath the Athabaska glacier would be a parabola of the form:

$$z = Ax^2 + c$$

or an ellipse: $$z = \pm \frac{b}{a} \sqrt{a^2 - x^2}$$

The origin is on the surface in the centre of the glacier. The semi-major axis is given in terms of "a", the distance from the centre to the edge of the glacier, and the semi-minor axis is "b", the central depth. These two models proved highly useful, particularly as the parabola gives a small side-wall angle while the ellipse provided a model with very steep sidewalls.

Figure 5 gives a comparison of the shape and theoretical gravity anomaly of a rectangular, elliptical and

parabolic cross section for the glacier at the approximate position of the borehole. One of the points to notice is that the gravity anomaly is still 4 to 6 milligals where the glacier has zero thickness. The zero-thickness anomaly varies considerably with both depth and shape. The zero thickness line can seldom be determined very accurately and it is often so close to the steep mountain sides that a gravity station cannot be located on it because the terrain correction will be uncertain by several milligals. Figure 5 also indicates that the gravity anomaly has the greatest rate of change near the edge of the glacier. These considerations will usually make it unwise to tie the Bouguer anomaly from the field data to the end points. The Bouguer anomaly does not give us information about the value of the zero ordinate for the glacier anomaly. All we have is a relative anomaly from the centre to the end station. The centre points have been tied together in any comparison of gravity anomalies from field or model studies. Figure 5 indicates that if the depth to the centre is known, the gravity data can predict the shape with considerable success.

The choice of depth on each line was guided by the information from one borehole and from a knowledge of the seismic results (personal communication from Professor

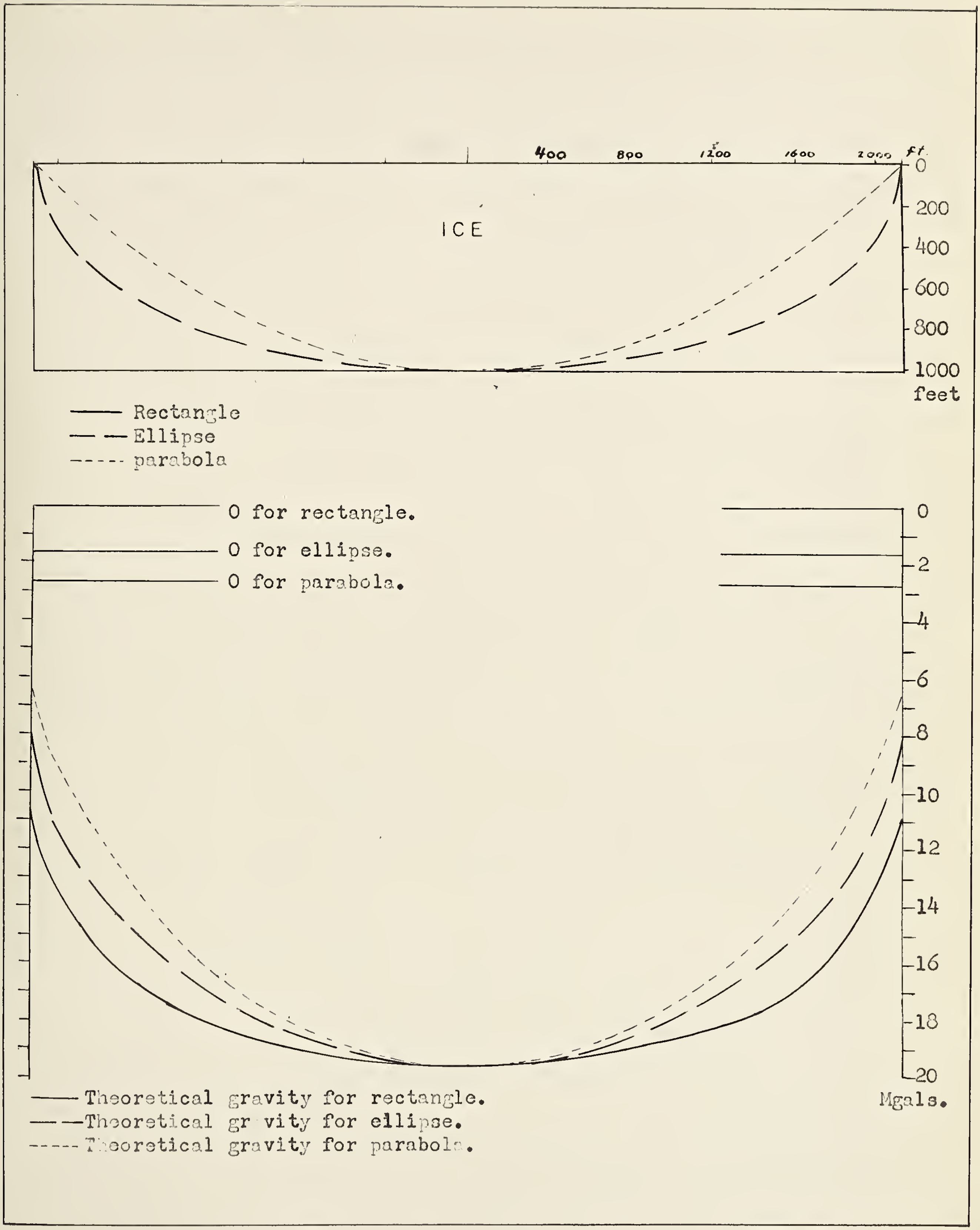


Figure 5. A comparison of the theoretical gr vity anomalies of three two-dimensional bodies. The bodies are 4280 feet wide along the surface (x direction); 1024 feet deep along the z direction and extend to infinity in the y diredtion. The density contrast is 1.77 gm/cc.

J. S. Savage). However, various other depths were modelled to check the seismic results and to obtain a value for the precision with which depth can be predicted by gravity results alone. Based on this work, a shallower depth was chosen on Lines A, E. H and G. The shape of the cross section was then determined on the basis of the gravity depth rather than the depth indicated by a preliminary interpretation of the seismic work.

As shown on page 32, the theoretical gravity anomaly of a two dimensional body with a parabolic cross section can be approximated as closely as required by the repeated use of the formula for the gravity of a rectangular prism (formula 8). This expression can easily be programmed for a digital computer to yield the theoretical gravity at any given point along a line on the surface.

Let the z axis pass through the center of the parabola in Figure 15. The symbols used will conform with those in formula 8 except for the appropriate subscripts.

h = maximum depth of the glacier

a = half width of the glacier at the surface

$t = D_1 - d_1$, the thickness of a rectangular prism

ξ_n = coordinate of observation point from the center of the glacier

n = number of observation points

$i = h/t$, number of rectangular prisms

The equation of the parabola is

$$z = Ax^2 + C$$

or
$$z = -\frac{h}{a^2} x^2 + h$$

$$\frac{b_i}{2} = x = a\sqrt{1 - \frac{z_i}{h}}$$

$$D_i = z_i + t$$

$$d_i = z_i - t$$

For a particular observation point, ξ_n ;

$$x_i = |\xi_n| + \frac{b}{2}$$

The program is designed to choose a given depth, h, and observation point, ξ_n , and compute formula (8) for each of the i rectangular prisms. It sums these up and prints out the answer. The process is repeated for all n observation points and for each maximum depth, h.

A program involving the above equation was written for the LGP-30 digital computer and carried out for 15 observation points along Line C. The thickness of the prisms was chosen to be 50 feet. For a determination of the best fit, the Bouguer anomaly of the center station was tied to the theoretical gravity value. The root

mean square of the deviations from the theoretical values was computed for each of the maximum depths. The results are summarized in Table VIII.

TABLE VIII Results of Two Dimensional Computer Program

Line C - 15 observation points

Depth (feet)	Root Mean Square of Deviations of Theoretical from Observed Gravity (milligals)
800	0.80
900	0.67
1000	0.54
1100	0.51
1200	0.54
1300	0.60

From a seismic program and from two nearby boreholes which reached bedrock, the depth is known to be 1050 $\pm$ 30 feet. On the basis of the above analysis a depth of 1100 would have been chosen.

The procedure illustrated above can be used in a systematic way on the central part of any glacier for which the observed gravity anomaly is known to the required accuracy. The expression for the gravity of a

rectangular prism can be adapted to an elliptical cross section with equal ease. If the Bouguer anomalies are asymmetrical, a similar degree of asymmetry can be programmed into the basic parabolic or elliptic cross section and the maximum depth determined from the smallest root mean square of the deviations as in the example given above.

4.4 Computer Program for the Gravitational Attraction of Body With Finite Dimensions

Once a two dimensional approximation has been found for the glacier the body of ice can be treated as an irregular, three dimensional ore body whose gravity anomaly can be computed by a method developed by Talwani and Ewing. (See the top diagram in Figure 6.) A contour map of the model of the glacier is drawn up and each contour is replaced by a horizontal irregular n-sided polygonal lamina as shown in the middle diagram of Figure 6. The contour interval used was 100 feet. The polygon should fit the contour map closely if an observation point is nearby. Let m be the number of observation points with coördinates (ξ_j η_j) and elevation E_j, $1 \leq j \leq m$. Let n be the number of points which define the corners of the lamina with coördinates (X_i, Y_i) and elevation E_i', $1 \leq i \leq n$. The coördinates of the

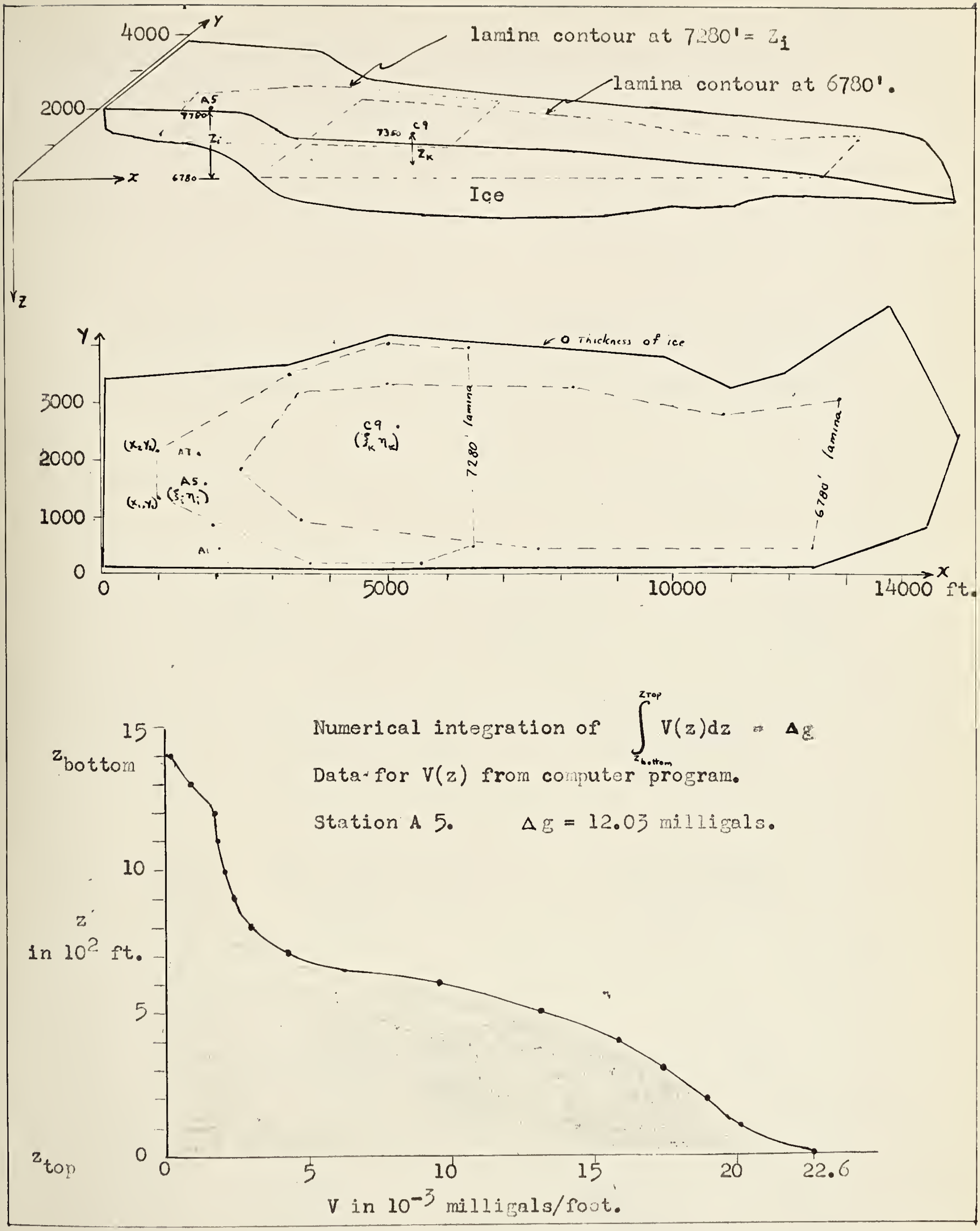


Figure 6. Geometry for the evaluation of the gravity anomaly caused by the density contrast between ice and bedbrock. V is gravity anomaly at a point (A-5) due to a horizontal lamina at depth z.

lamina are translated so the origin of the cartesian axis is at the observation point $(\xi_j \ \eta_j)$.

$$x_i = X_i - \xi_j$$

$$y_i = Y_i - \eta_j$$

$$z_i = E_j - E_i$$

Following Talwani and Ewing, formula (4) was reduced to a form suitable for evaluation by a digital computer.

$$V = k\delta \sum_{i=1}^{n} \left[W \text{ arc cos} \left\{ \frac{x_i}{r_i} \frac{x_{i+1}}{r_{i+1}} + \frac{y_i}{r_i} \frac{y_{i+1}}{r_{i+1}} \right\} \right.$$

$$\left. - \text{arc sin} \frac{z \, q_i S}{\sqrt{p_i^2 + z_i^2}} + \text{arc sin} \frac{z \, f_i S}{\sqrt{p_i^2 + z_i^2}} \right] \tag{10}$$

$$b_i = \frac{y_i - y_{i+1}}{r_{i,i+1}} x_i - \frac{x_i - x_{i+1}}{r_{i,i+1}} y_i$$

$$q_i = \frac{x_i - x_{i+1}}{r_{i,i+1}} \frac{x_i}{r_i} + \frac{y_i - y_{i+1}}{r_{i,i+1}} \frac{y_i}{r_i}$$

$$f_i = \frac{x_i - x_{i+1}}{r_{i,i+1}} \frac{x_{i+1}}{r_{i+1}} + \frac{y_i - y_{i+1}}{r_{i,i+1}} \frac{y_{i+1}}{r_{i+1}}$$

$$m_i = \frac{y_i}{r_i} \frac{x_{i+1}}{r_{i+1}} - \frac{y_{i+1}}{r_{i+1}} \frac{x_i}{r_i}$$

$$r_{i,i+1} = \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2}$$

$$r_i = \sqrt{x_i^2 + y_i^2}$$

$$r_{i+1} = \sqrt{x_{i+1}^2 + y_{i+1}^2}$$

$S = +1$ if p_i is positive. $S = -1$ if p_i is negative.

$W = +1$ if m_i is positive. $W = -1$ if m_i is negative.

The program prints out a table of Z_j, ξ_j, η_j, and V_j for each lamina and then reads the data for the next lamina.

A glacier is a unique case of an "ore" body because the observation points straddle the "ore" body itself. Therefore, only the lamina below the observation point need be computed. The material above the level of the observation point has been removed by the terrain corrections.

As written for the LGP-30 computer, the program is in fixed point and the coördinates of the observation points should be less than 30,000 feet. The time to

compute one lamina is 10n seconds per observation point, where n is the number of sides to the lamina. The value of $k\delta$ is $6.667 \cdot 10^{-8}$ $cm^3/gm.\ sec^2$. 1.77 gm/cm^3 or $3.597 \cdot 10^{-3}$ milligals per foot.

Two models were computed for each of the 8 lines. For the majority of the lines, the second model was 20% shallower up-dip from the line in question. In addition, 2 extra models were determined for lines B and D to provide a better fit. The total computer time for 45 observation points for the two models was 13-1/2 hours. Two hours of extra computer time was required to adjust the fit on lines B and D. Including the time required to determine the coördinates of the observation points and lamina, the program was not completed significantly faster than it could have been done with Siegert's mechanical integrator. However, modification to the model requires little change to the input data and can be done very quickly. The LGP-30 is a very slow computer and a larger model would complete the task in a fraction of the time.

Formula (3) for the gravity anomaly caused by the whole glacier was not programmed. The bottom diagram of Figure 6 illustrates the numerical integration for one observation point.

4.5 Results

The results of the computer program are presented in Table VI and Figures 7 to 12 inclusive. The top diagram is a transverse cross section of the glacier together with various other models computed for the purposes of comparison. The lower two graphs show a comparison of the observed gravity anomaly and the theoretical gravity anomaly of the model. The observed Bouguer gravity values did not have to be corrected for a regional gradient because the cross sections are along the strike of geologic structures. This is confirmed by a regional gravity survey in the area (Garland and Tanner, 1957). The final model, shaded in grey, was generally interpolated from the computed model to give a better fit than is illustrated by the anomaly curve.

The A line appears to be slightly shallower than the seismic data would indicate. However, the seismic shot point was off the line at L 10 so it is not possible to make an exact quantitative comparison. Transverse cross sections were determined seismically on Lines D and C and this data agrees within ± 100 feet. The main difference is that the cross section determined by gravity is notably smoother than the seismic section.

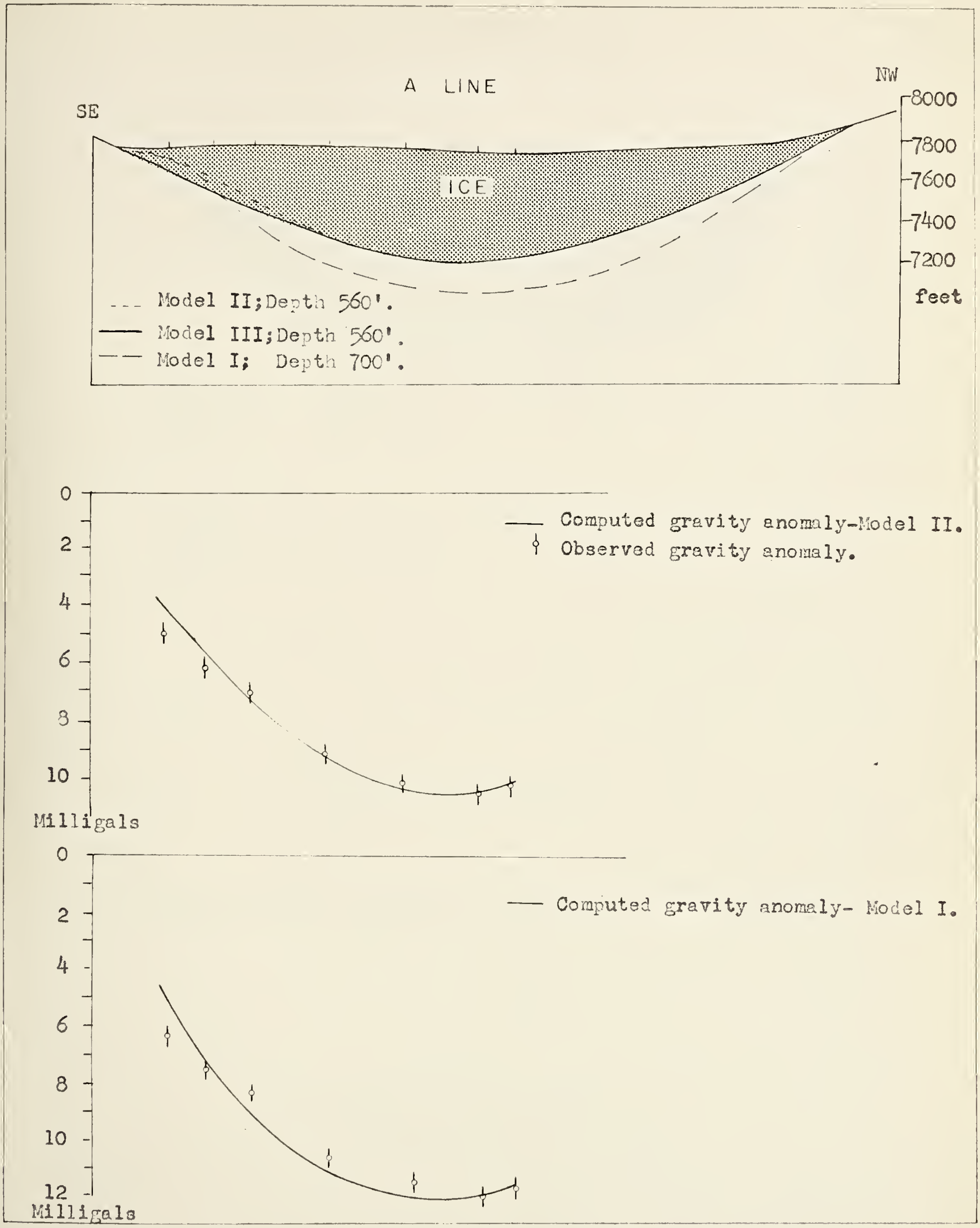


Figure 7. Cross section of the Athabaska Glacier together with the theoretical and observed gravity anomaly. Model III is the best fit according to gravity data. Horizontal and Vertical scales are equal.

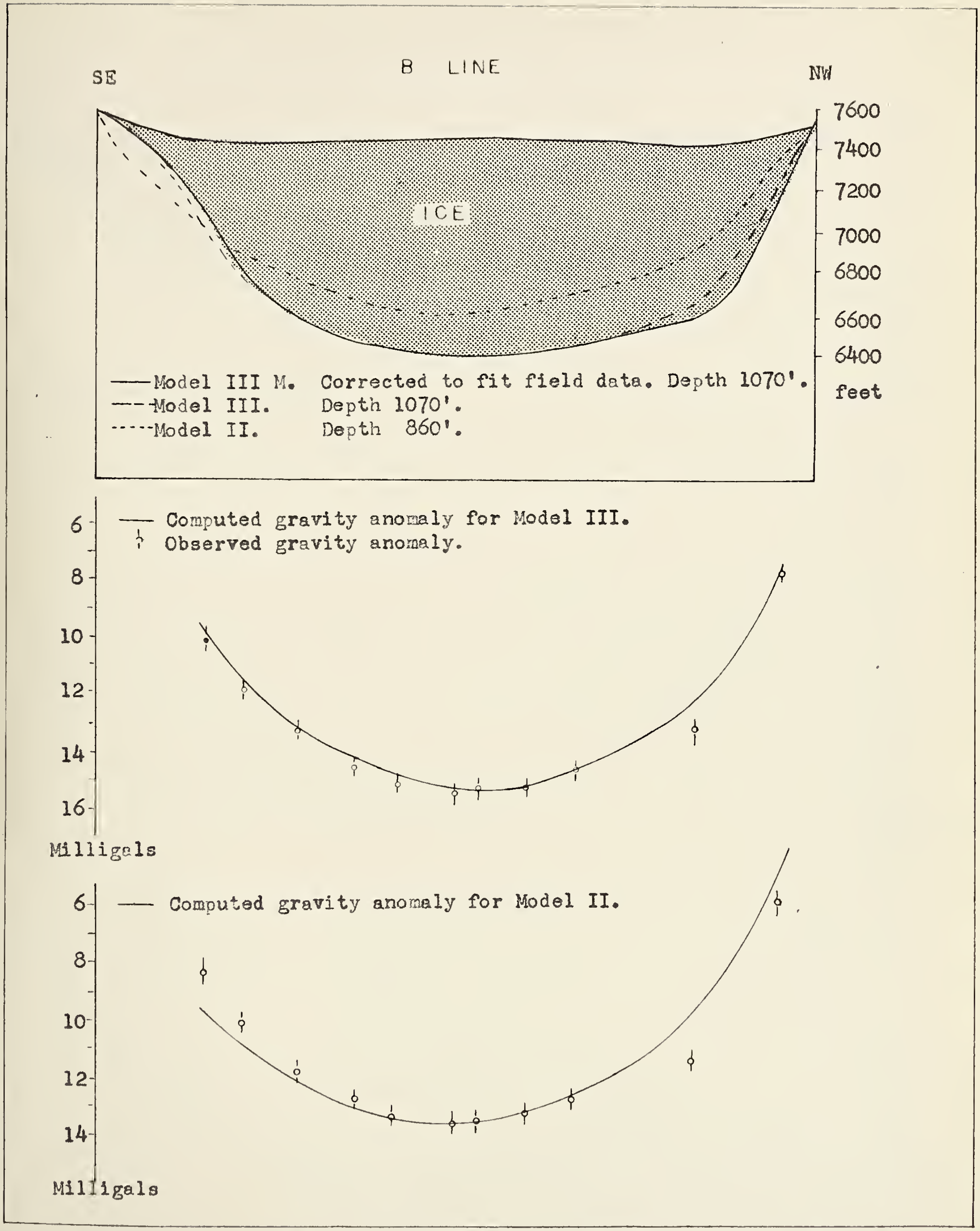


Figure 8. Cross section of the Athabaska Glacier together with the theoretical and observed gravity anomaly. Model III M is the best fit according to gravity data. Horizontal and Vertical scales are equal.

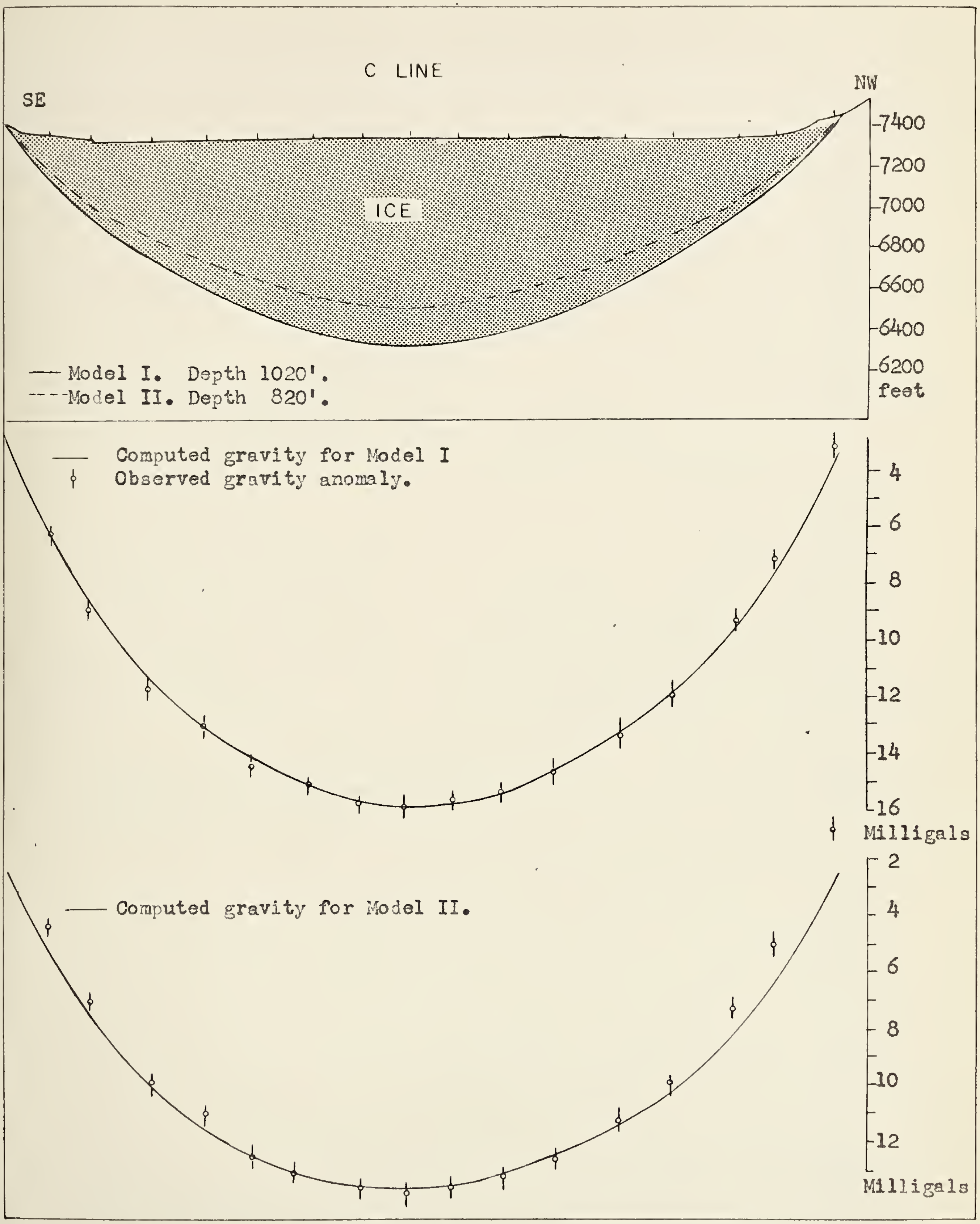


Figure 9. Cross section of the Athabaska Glacier together with the theoretical and observed gravity anomaly. Model I is the best fit according to gravity data. Horizontal and vertical scales are equal.

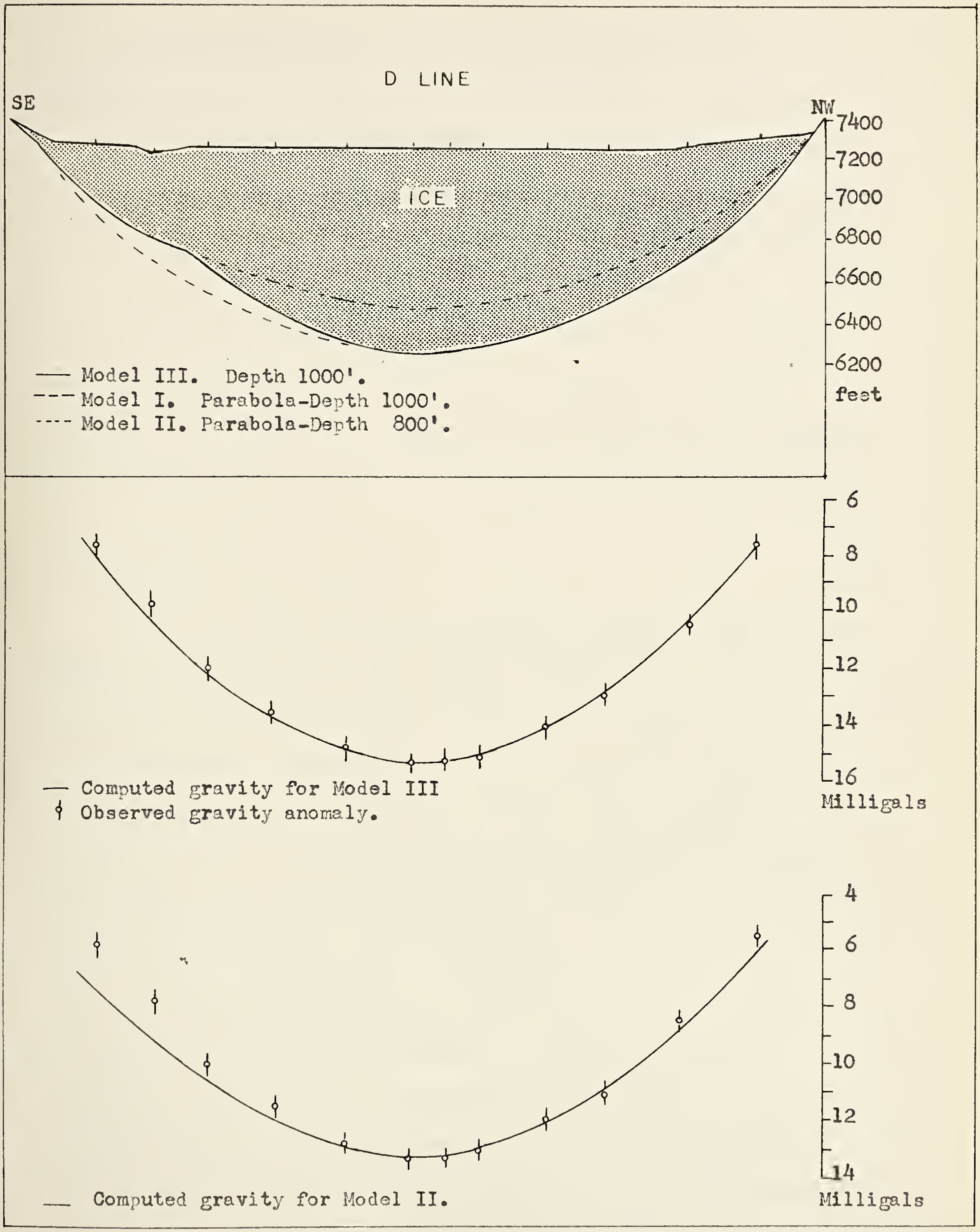


Figure 10. Cross section of the Athabaska Glacier together with the theoretical and observed gravity anomaly. Model III is the best fit according to gravity data. Horizontal and vertical scales are equal.

Lines E and H are 10% shallower than seismic data indicates. The longitudinal seismic section indicates that the bedrock is quite rough in this section and, as expected, gravity data tends to smooth out the irregularities. The longitudinal profile based on gravity data (Figure 13) is everywhere within ± 50 feet of the seismic data between lines B to D and within ± 100 feet between lines D to F. Line F is remarkable for its shallowness. The deeper model (450') which was programmed to check this does not fit the field data but the fit is quite good for the model with a depth of 370 feet (Figure 12).

The value of three dimensional computations is best illustrated on lines near the terminus of the glacier. It was possible to assign an absolute value to the anomaly produced by the field data by means of a station at the foot of the glacier. The terrain correction here is certainly accurate within 0.2 milligals and the absolute depth should be accurate within ± 10%. The seismic record has a poor reflection at a depth of about 490 feet. As illustrated on the bottom of Figure 12, this is incompatible with the gravity results. Models were programmed for a depth of 1/2 and 1/3 the seismic depth to check on multiple reflections. On the basis of the gravity study the reflection appearing

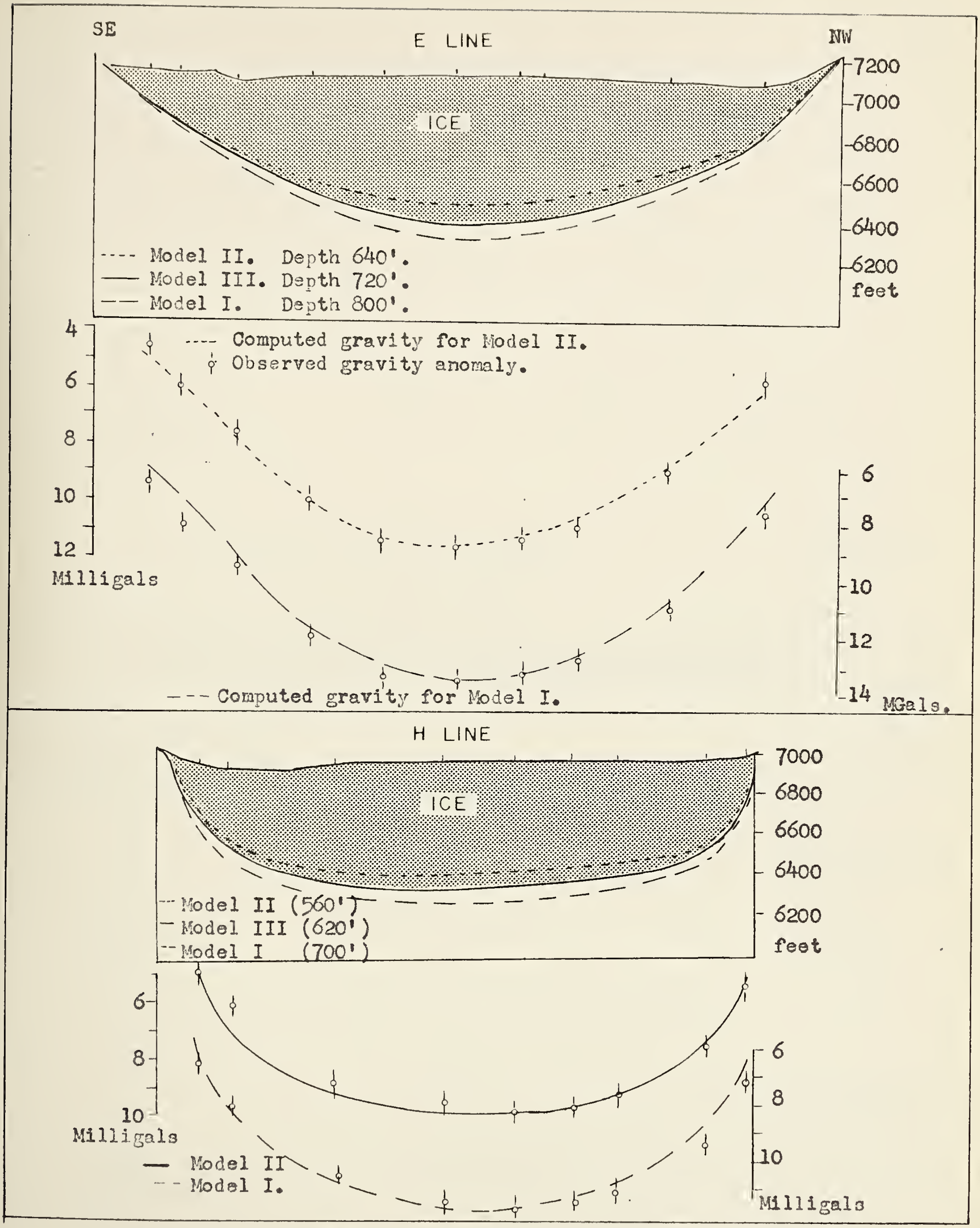


Figure 11. Cross section of the Athabaska Glacier together with the theoretical and observed gravity anomaly. Model III is the best fit according to gravity data. Horizontal and vertical scales are equal.

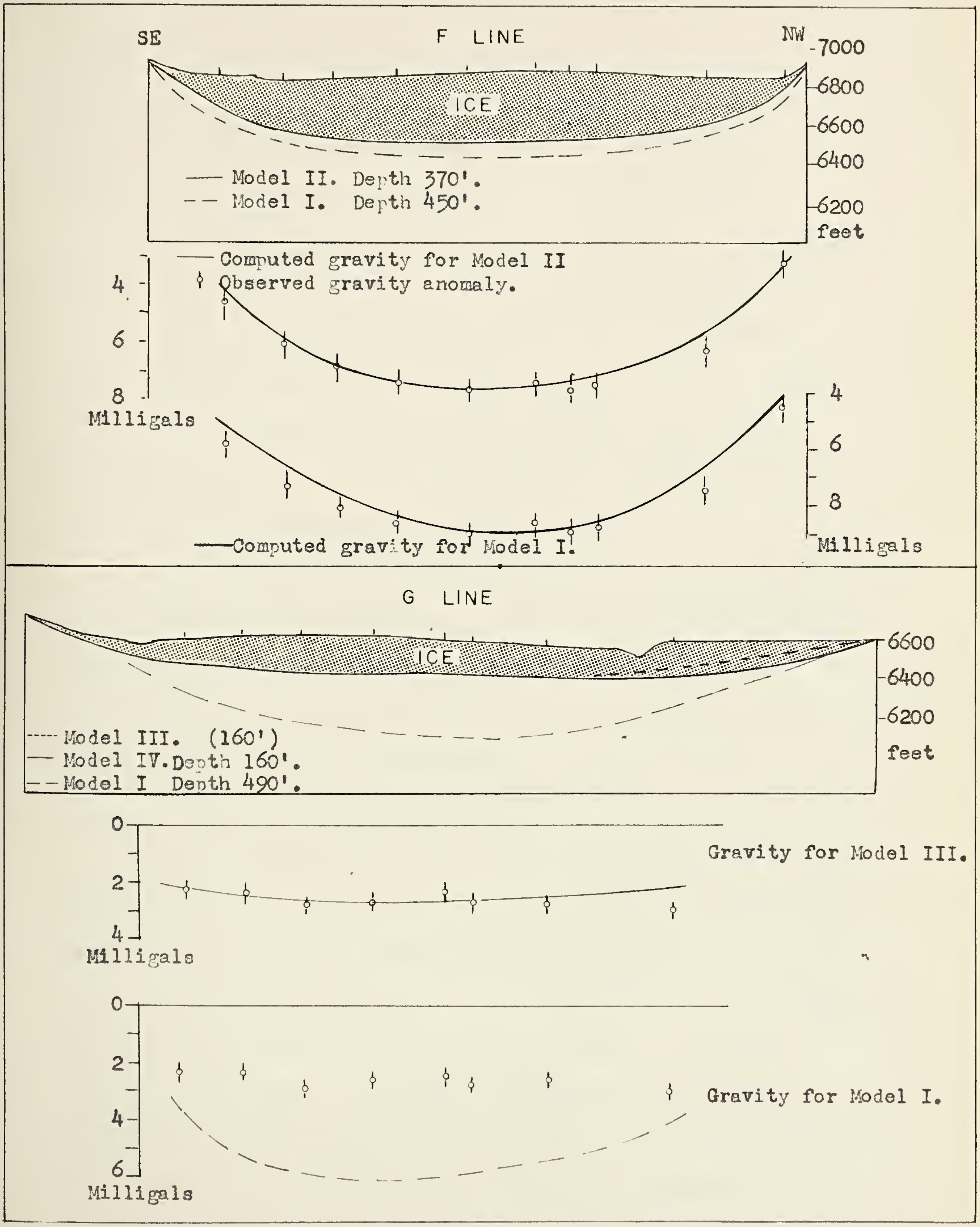


Figure 12. Cross section of the Athabaska Glacier together with the theoretical and observed gravity anomaly. Model II fits best for the F Line and Model IV for the G Line. Horizontal and Vertical scales are equal.

on the record is the second multiple. The primary reflection should appear at 0.27 seconds (+phase lag due to filtering). The primary reflection and its first multiple are probably obscurred by surface waves.

The deepest part of the glacier is on a line through B 6, C 8 and D 6. This is best seen by a comparison of the Bouguer Map, Figure 3(Appendix), and the Isopach Map, Figure 4 (Appendix). The position of Line L was chosen on the basis of a week's study of the stake movement on Line C (See Table 1) and is only about 200 feet from the deepest part of the glacier.

The cross section of the glacier at lines C and E is very nearly a parabola. Line F has a cross section midway between an ellipse and a parabola. At Line H the glacier narrows appreciably and the shape of the cross section closely resembles an ellipse. Lines B and D have cross sections which are more irregular.

The top diagram in Figure 13 (Appendix) shows the Bouguer anomaly along Line L, the central, longitudinal traverse. It gives a qualitative representation of the thickness of the glacier. It is now possible to subtract the gravity anomaly of the glacier from the Bouguer anomaly and obtain a residual Bouguer anomaly which should reflect the underlying geology. (Use was made of Table VI - Results of Computer Program, Appendix). If

the glacier computations have been properly made, the remaining curve should be very smooth and become more negative to the southwest. This negative trend into the Rocky Mountain Trench is shown on a Bouguer Gravity Map of British Columbia and Alberta (Garland and Tanner, 1957). The residual anomaly is indeed as described above. However, between lines H and G the anomaly decreases faster than the regional rate and indicates less dense material under the bulk of the glacier. The inflection point is on Line F which has a pronounced bump on the glacier floor. These features may be related to the structural geology of the underlying section but not enough is known about the density and the stratigraphic sequence to make a more definite statement.

5. APPLICATION OF THE RESULTS TO GLACIOLOGY

In 1949 Orowan made some calculations on the yield stress of the ice by assuming the ice behaved as an idealized plastic solid. J. F. Nye (1951, 1957) has developed this theory much further and derived equations for the stress distribution and the velocity of a two dimensional slab of ice flowing down a gently undulating rough slope. Deformation is assumed to be negligible below a critical yield stress and the shear stress does not rise above this value.

Allow a two dimensional wedge of ice, with surface slope, α , to rest on a rough inclined surface of slope, β, as shown in the diagram below. The ice cannot slide down except by internal plastic shear.

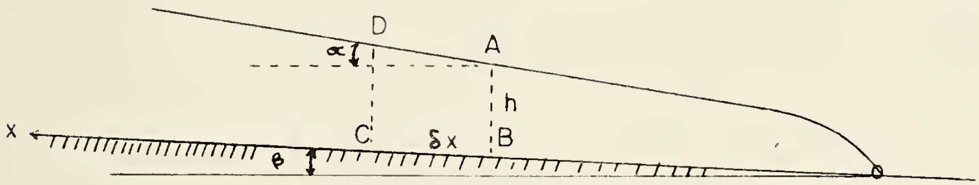


Figure 16

Following Nye's (1952 C) analysis, the approximate mean normal pressure on AB is $\frac{1}{2}\rho g h$ where ρ is the density and g is the gravitational acceleration. The normal force on AB is $\frac{1}{2}\rho g h^2$. The normal force on DC is $\frac{1}{2}\rho g h^2 + \frac{d}{dx}(\rho g h^2)\delta x$. The force parallel to the bed is $\tau(\delta x)$ where τ is the shear force per unit area exerted by the bed on the ice and the component of weight of the section is $h(\delta x)\rho g \sin\beta$. To a first approximation:

$$\frac{d}{dx}\left(\frac{1}{2}\rho g h^2\right)\delta x + \rho g h \cdot \beta \cdot \delta x = \tau \cdot \delta x$$

or

$$\frac{dh}{dx} + \beta = \frac{\tau}{\rho g h}$$

$\left(\frac{dh}{dx} + \beta\right)$ is the slope of the upper surface, α , therefore:

$$\tau = \rho g h \alpha \tag{11}$$

The thickness must satisfy the following simple equation:

$$h = \frac{h_o}{\alpha} \tag{12}$$

where $$h_o = \frac{\tau}{\rho g}$$

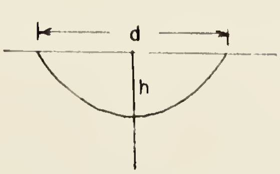
Nye (1952 C) has modified this formula to take into account the sides of the glacier valley. In a glacier of arbitrary but constant cross section, the average value of shear stress, τ_a , at the bed was found to be:

$$\begin{aligned} \tau_a &= \rho g R \sin \alpha \\ R &= \frac{A}{P} \end{aligned} \tag{13}$$

where A is the area of the cross section perpendicular to the bed, and P is the perimeter of this cross section. The formula is approximately true if the cross section varies slowly and the current value of R and the surface slope, α ,are used.

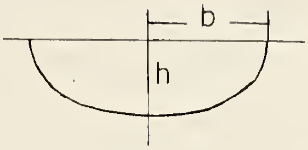
If the cross section is a parabola:

$$\begin{aligned} P &= \frac{d^2}{8h}\left[\sqrt{c(1+c)} + 2.3026 \log_{10}\left(\sqrt{c} + \sqrt{1+c}\right)\right] \\ c &= \left[\frac{4h}{d}\right]^2 \\ A &= \frac{2}{3} dh \end{aligned} \tag{14}$$



If the cross section is an ellipse:

$$P \doteq \pi\sqrt{\frac{b^2+h^2}{2}}$$



$$A = \frac{\pi}{2}bh$$

If the cross section is irregular in shape, approximate methods must be used to find the perimeter and area. All of the quantities above are known and it was possible to calculate the shear stress at the bed on Lines B, C, D, E. H and F. The gravitational constant was taken to be 981 cm/sec^2 and the density was 0.90 gm/cm^3.

TABLE VII. Average Shear Stress on the Bedrock

Line	Depth (h) (meters)	Width (d) (meters)	R (meters)	α °	α '	τ_a (10^6 dynes/cm^2)
B	326	1055	170	3	24	0.9
C	310	1290	181	4	5	1.1
D	305	1170	172	3	51	0.8
E	219	1085	133	5	17	1.1
H	189	926	119	5	42	1.0
F	113	988	74	5	17	0.6
				Mean		0.9

The bedrock on Line F was particularly rough and erratic and if we omit this low value, the average shear stress at the bed for the 5 upper lines becomes 1.0 bars (1 bar = 10^6 dynes/cm^2). Nye (1952 b) has made calculations for sixteen Alpine glaciers and finds values ranging from 0.49 to 1.51 bars. The values above are in the middle of Nye's range and show a remarkably small variation. Glen (1952) has used uniaxial compressional and tensional stresses of 1.5 to 10.0 bars in the laboratory to produce strain rates similar to those observed on glaciers.

Now that we have an average value for the shear stress and have seen that it does not depart much from a value of 1.0 bars, we can make use of relation (12) to determine the thickness of the glacier. The value of the constant h_o becomes 11.3 meters or 37.1 feet. Formula (12) then gives a depth of 750 feet for D line and 400 feet for E line. The frictional resistance of the sides of the valley has been neglected in this simple expression so the estimated depth is too small as expected.

In point of fact, formula (12) may be used to calculate the thickness of an ice sheet if the only information available is the surface slope (Nye, 1952 a). For the relation to be satisfied, the sheet of ice must

be known to be moving. An area which satisfies this condition is the Snow Dome on the Columbia Icefields. It has an average slope of 10° to 11° according to the Boundary Survey maps. The estimated depth of ice on this feature is deduced to be about 200 feet.

Reference to Figure 13 discloses that the glacier above Line B has a steep gradient while below Line B the slope is very small and even becomes negative. If some section of the glacier becomes thicker than required by equation (12), this section will exert a pressure on the part of the glacier that is too thin and relation (12) will be re-established by flow. According to Orowan (1949), the additional longitudinal force required for pushing the glacier along over the low gradient part may be so large that it exceeds the resistance of the ice to longitudinal compression. Longitudinal compression of the glacier takes place and the glacier thickens until the cross section is large enough to transmit the longitudinal force without the longitudinal yield stress of the ice being exceeded.

6. CONCLUSIONS

The thickness of the Athabaska glacier has been obtained along eight transverse lines by an investigation of the gravity anomalies. Previous workers have obtained

the depth with a precision that varied from -10% to +25% or in some cases +40%. A higher degree of accuracy was attained in this study by making detailed terrain corrections and by treating the glacier as a three dimensional ore body. The Bouguer gravity anomalies were determined within 0.5 milligals or better and the depth values are believed to be accurate within -10% to +15%. The shape of the bedrock can be determined within about $\pm$ 10% if the central depth is known from other sources and the edge of the glacier can be determined accurately.

The major disadvantage of the method is that it requires a large scale contour map of the area to reduce the terrain corrections. This problem is rapidly being overcome for most mountainous regions by the use of aerial photogrammetry. Making the terrain corrections is a long and tedious operation but this can be overcome by use of Siegert's gravity integrator or by the use of a digital computer with a large storage capacity.

Previous depth determinations were limited to the smooth, central, portion of a glacier since a two dimensional model was used in the computations. Three dimensional computations with a low speed computer were made in this study and the depth near the terminus of the glacier and in the upper elevated section was obtained.

The depth of the Athabaska glacier varied from 1070 feet on line B to 160 feet on line G.

The gravity method is a valuable adjunct to a seismic survey since a detailed set of measurements can be obtained more economically. In crevassed areas where seismic reflections are difficult to obtain and in areas where multiple reflected events are recorded the gravity method has a distinct advantage.

In making depth computations, a useful first approximation to the cross section of the valley of a glacier is a parabola. The cross section of the valley through which the Athabaska glacier flows has been found to approximate a parabola along several of the lines. Svensson has noted that the shape of some glacial valleys also approximates a parabola. It is well known that glaciers alter originally stream-cut valleys from a V to a U-shaped profile. This evidence would seem to indicate some theoretical significance to a parabolic shape.

A basin has been formed in the center of the glacier, probably by some form of erosion so that the glacier now flows along a surface that is flat or slopes slightly upwards toward the terminus. Combined gravity and seismic data suggest a similar up-valley slope on the first step of the glacial stairway. If the glacier

should disappear entirely, the chain of basins would form "paternoster" lakes. The glacier has thickened to its maximum extent in the central region so that it now has a surface slope which allows it to flow along the nearly level valley floor.

From a knowledge of the depth, shape and surface slope of the glacier, the average shear stress exerted by the bed on the ice was found to be 1.0 bars.

BIBLIOGRAPHY

BIBLIOGRAPHY

Allan, J. A., 1938. Cambrian in the Vicinity of Sunwapta Pass, Jasper Park, Alberta. Royal Society of Canada, Vol. 32, Section LV, pp. 113-121.

Bull, C. and Hardy, J. R., 1956. The determination of the thickness of a glacier from measurements of the value of gravity. Journal of Glaciology, Vol. 2, pp. 755-762.

Bullard, E. C., 1935. Gravity Measurement in East Africa. Phil. Trans. of Royal Society Series A, Vol. 235.

Collier, E. P., 1958. Glacier Variation and Trends in Run-off in the Canadian Cordillera. Publication No. 46 De L'Association Internationale D'Hydrologie Scientifique. General Assembly of Toronto, Vol. IV, 1957, pp. 344-357.

Garland, G. D. and Tanner, J. G., 1957. Investigations of Gravity and Isostasy in the Southern Canadian Cordillera. Publications of the Dominion Observatory, Ottawa, Vol. XIX, No. 5.

Gerrard, J. A. F., Perutz, M. F., and Roch, A., 1952. Measurement of the velocity distribution along a vertical line through a glacier. Royal Society, London, Proc. A, Vol. 213. pp. 546-558.

Glen, J. W., 1952. Experiments on the Deformation of Ice. Journal of Glaciology, Vol. 2, No. 12, pp. 111-114.

Heiland, C. A., 1940. Geophysical Exploration. Prentice-Hall Inc., New York.

Hubert, M. K., 1948. A Line-Integral Method of Computing the Gravimetric Effects of Two Dimensional Feature. Geophysics, Vol. XIII, pp. 226-254.

Hughes, R. D., 1955. Geology of Portions of Sunwapta and Southesk Map Area, Jasper National Park, Alberta, Canada. Guidebook Fifth Annual Field Conference, Alberta Society of Petroleum Geologists, pp. 69-116.

Jacobs, J. A., Grant, F. S., and Russell, R. D. Gravity Measurements on the Salmon Glacier, British Columbia and Adjoining Snow Field, British Columbia. B.G.S.A., 1960, Vol. 71, pp. 1223-1230.

Littlewood, C. A., 1952. Gravity Measurements on the Barnes Icecap, Baffin Island, Arctic, Vol. 5, pp. 118-124.

Margeneau, H. and Murphy, G. M. The Mathematics of Physics and Chemistry. Random Walk, p. 442.

Matthes, E. F., 1942. Glaciers. Chapter 5 of Hydrology. Edited by O. Meinzer. Physics of the Earth, Vol. 9, Dover Publication, pp. 149-219.

Nettleton, L. L., 1940. Geophysical Prospecting for Oil. McGraw-Hill Book Company, Inc., New York.

Nye, J. F., 1951. The flow of glaciers and ice-sheets as a problem in plasticity. Royal Society of London, Proceeding, Series A, Vol. 207, pp. 554 -572.

________, 1952a. A Method of Calculating the Thicknesses of the Ice-Sheets. Nature, Vol. 169, pp. 529-530.

________, 1952b. The mechanics of glacier flow. Journal of Glaciology., Vol. 2, pp. 82-93.

________, 1952c. A comparison between the theoretical and measured long profile of the Unteraar Glacier. Journal of Glaciology, Vol. 2, pp. 103-107.

________, 1957. The distribution of stress and velocity in glaciers and ice-sheets. Royal Society of London, Proceedings, Series A, Vol. 239, pp. 113-133.

Orowan, E., 1949. Journal of Glaciology, Vol. 1, pp. 231-237.

Raymond, P. E., 1928. Two new Cambrian trilobites. American Journal of Science, Vol. 15, p. 309.

Seligman, G. and Mercanton, P. L., 1950. The specific gravity of ice. Journal of Glaciology, Vol. 1, No. 8, p. 459.

Severson, J. L., 1950. Devonian Stratigraphy, Sunwapta Pass Area, Alberta, Canada. American Association of Petroleum Geologists Bulletin, Vol. 34, No. 9, pp. 1826-1849.

Shumsky, P. A., 1960. Density of glacier ice. Journal of Glaciology, Vol. 3, No. 27, pp. 568-576.

Siegert, A. J. F., 1942. A mechanical integrator for the computation of gravity anomalies. Geophysics, Vol. VII, pp. 354-366.

Stutfield, H. E. M. and Collie, J. N., 1903. Climbs and Explorations in the Canadian Rockies. Longmans, Green and Co., London, pp. 103-122.

Svensson, H., 1959. Is the Cross Section of a Glacial Valley a Parabola. Journal of Glaciology, Vol. 3, No. 25, March, pp. 362-363.

Talwani, M. and Ewing, M., 1960. Rapid Computation of Gravitational Attraction of Three Dimensional Bodies of Arbitrary Shape. Geophysics, Vol. XXV, pp. 204-225.

Thiel, E., LaChapelle, E., and Behrendt, J., 1957. The Thickness of Lemon Creek Glacier, Alaska, as Determined by Gravity Measurements. Transactions, American Geophysical Union., October, 1957, Vol. 38, No. 5, pp. 745-749.

Wheeler, A. O., 1921. The Application of Photography to the Mapping of the Canadian Rocky Mountains. Canadian Alpine Journal, Vol. 11, pp. 76-87.

________, 1921. Notes on the Glaciers of the Main and Selkirk Ranges of the Canadian Rocky Mountains. Canadian Alpine Journal, Vol. 11, pp. 137-140.

Williams, M. B., 1940. Jasper National Park. H. R. Larson Publishing Co, Hamilton.

PART II

A GRAVITY INVESTIGATION OF THE ROCKY MOUNTAIN TRENCH IN SOUTHERN BRITISH COLUMBIA

1. INTRODUCTION

A regional gravity investigation of the Southern Cordillera was undertaken by Garland and Tanner in 1954. Gravity measurements obtained in the Rocky Mountain Trench indicated areas with a considerable thickness of fill. It is the purpose of this investigation to examine the Trench between Cranbrook and the International Boundary with a more detailed set of gravity measurements. The objective was a more accurate delineation of depressions in the bedrock which are filled with low density fill and a search for other anomalies associated with faulting and intrusion. An interpretation is made of a gravity lineation discovered along the Moyie Lenia fault.

2. GEOLOGY OF THE AREA

The Rocky Mountain Trench is a prominant linear depression separating the Rocky Mountain system on the east from the Purcell, Selkirk, Monashee, Cariboo, Omineca and Cassiar ranges on the west. (See Figure 1a.) It extends from Flathead Lake in Montana to the British Columbia-Yukon border. The term "Trench" was defined by Daly (1912) as a "long, narrow, intermontane depression occupied by two or more streams alternately draining the depression in opposite directions."

In the area under study the rocks in the Purcell range consist of over 30,000 feet of quartzites, argillites and limestones called the Purcell series. (See Table Ia.) These sediments are of Precambrian Beltian age. Basalt flows called the Moyie intrusives and extrusions of andesitic lava and tuff interrupt the sedimentary sequence. The section is arched up to form the northward plunging Purcell geanticline. Near Cranbrook the geanticline is cut by several transverse faults, the most important of which is the Moyie Lenia fault.

Kirkham believes the Moyie-Lenia is an overthrust fault with the west block moving upward along a plane

TABLE Ia. Table of Formations
(following Leech 1958)

ERA	PERIOD OR EPOCH	Formation	Lithology	Thickness (feet)
CENOZOIC			sand, alluvium, till, gravel	
MESOZOIC	Lower Cretaceous ?		monzonite, granodiorite	
PALAEOZOIC	Mississippian	Rundle Gp.	limestone	2500
		Banff	silty limestone	1300
		Exshaw	black shale	57
	Devonian	Palliser Gp.	massive limestone	800
		Alexo	sandy limestone	1335 (Alexo and Fairholme)
		Fairholme	limestone	
		Harrogate	black limestone	
		Burnais	gypsum, dolomite	600
		"Basal" unit	sandy dolomite	
	+ + + + +	UNCONFORMITY + + + + + + +		
	Silurian to Middle Cambrian	Beaverfoot-Brisco, Wonah, Glenogle, McKay, Jubilee, Elko, and Burton.		
	Lower Cambrian	Eager	shale, limestone, ss.	
		Cranbrook	quartzite	
+ + + +	+ + + + +	UNCONFORMITY + + + + + + +		
PRECAMBRIAN	Purcell?	Moyie intrusion	meta-diorite	
	Upper Purcell	Dutch Creek	dolomitic argilites & ss.	3000
	Lower Purcell	Purcell extrusions	andesitic lava & tuff	465
		Siyeh	argillite	7000 (Siyeh and Kitchener)
		Kitchener	dolomitic argillites	
		Creston	argillites, quartzites	5000-6000
		Aldridge	argillites, quartzites	8000
		Fort Steele	white quartzite	6000+

never less than 45° in slope. Rice (1937) states that the dip is 60° west at Peavine Creek at the north end of Moyie Lake. The Aldridge formation on the west lies against the Siyeh on the east to give a vertical displacement of about 15,000 feet. The Moyie Lenia fault has been closely positioned by Leech in the Joseph Creek area south of Cranbrook (written communication, see Figure 2a, In pocket).

The Purcell series occupies the entire western edge of the Rocky Mountains in this area. The broad structure indicates that this forms the east flank of the Purcell geanticline but locally there are many small folds and the area is complicated by faulting. The Dibble Creek fault enters the Trench transversely southeast of Fort Steele. Leech (1959) considers that the north block had a relative upward and eastward movement and that lubrication was provided by Devonian gypsum (Burnais formation) in the footwall. In the Rocky Mountain ranges northeast of the Dibble Creek fault, Devonian rocks lie on Silurian, Ordovician and Cambrian beds but south of the fault, the Devonian lies on a few feet of Cambrian or directly on the Kitchener-Siyeh formation.

The floor of the Trench between Bull River and Sand Creek contains outcrops of Devonian and Mississippian strata. (See Figure 4a). Schofield (1951) found these

to rest unconformably on the Precambrian Gateway formation west of Wardner at Gold Creek. The same sequence of Devonian-Mississippian rocks reappears in the Lizard range south of the Sand Creek Fault.

Important faults have been traced in the Trench between Bull River and Galloway (Leech, 1958). A longitudinal west dipping fault separates the Purcell series in the Rockies to the northeast from the Palaeozoics in the trench. In addition, several transverse faults cut the Palaeozoic strata. Leech (1959) believes that the Palaeozoic rocks in the Trench "belong to an upper plate dropped along the west dipping fault at the east side of the trench rather than that they belong to a plate thrust from below." He also finds that the Precambrian rocks on the trench wall are themselves a thrust plate and partially underlain by Palaeozoic rocks.

Several small outcrops of altered monzonitic or granodioritic porphyry indicate a small stock near the mouth of the Bull River. Sheep Mountain, west of the confluence of the Elk and Wigwam Rivers, is intruded with igneous rock (written communication, Leech).

The trench has a thick veneer of glacial till, and indeed, glacial material is found over much of the area except on the highest peaks. The rivers have cut valleys several hundred feet deep through the material in the

Trench. A deposit of gravel, sand and silt known as the St. Eugene Silts occurs along St. Mary River. Schofield (1915) regarded these as interglacial or Pleistocene in age but Hollock and Berry consider them to be late Tertiary from a study of fossil plants. If this is so, they somehow escaped erosion by the ice. Rice (1937) points out several facts which point to little active erosion during the period of glaciation. These include the occurrence of V-shaped tributary valleys and placer gold deposits in morainic material.

3. THE GRAVITY MEASUREMENTS AND THEIR REDUCTION

3.1 The Gravity Survey

Observations were carried out with a Worden Gravity Meter which has a calibration constant of 0.2607 milligals per scale division. About 300 gravity stations have been established in the Cranbrook-Elko area. One-third of these are either from a traverse by Garland and Tanner in 1954 or by Garland in 1958. T. L. Thompson, a graduate geology student from Stanford, who was studying the structure in the vicinity of Bull River, made observations at 127 stations. The remainder of the observations were made in 1959 and 1960 by the author.

The readings were taken along highways, forestry trails, railroads, or at stream crossings and survey monuments. The location of the stations were spotted on

the Columbia River Basin maps which are on a scale of two inches to a mile or 1:31,680. The contour interval is 20 feet up to an elevation of 3000 feet. Maps on a scale of 1:40,000 or 1:50,000 with 100 foot contour interval were used for the remainder of the area. All gravity measurements were made with respect to the network of stations established by the Dominion Observatory (Garland and Tanner, 1954). Many ties were made between the stations obtained at different times and the results check within 0.2 milligals. A direct comparison can be made at stations 6, 10, 18, 23, 38, 161, 166, 184, 204, 208 and 211.

Gravity and aneroid barometer readings were made in loops from a base station and repeated at least once every two hours. A linear drift rate was assumed for both meter and barometer and the readings at new stations were corrected for this drift. The barometer readings were used whenever station elevations were not available from bench marks and spot highway elevations. The elevation of most of the stations obtained in this manner are believed accurate within 5 feet but some may be as much as 10 feet off. However, one line of stations (Numbers 47 to 58 inclusive) is in doubt by $\pm$ 35 feet. The Bouguer values on this line may be in error by $\pm$ 2.1 milligals. The station locations are believed accurate within about 500 feet.

3.2 The Reduction of the Gravity Measurements

The principal facts for the gravity stations are set out in Table IIa. This table gives the station, field number, longitude, latitude, elevation, observed gravity and the corrections necessary to obtain the Bouguer anomaly. The theoretical gravity at sea level, γ, was obtained from the 1930 International Gravity Formula (Nettleton, 1940). The free air and Bouguer correction amounts to 0.060 milligals per foot above sea level. A density of 2.67 gms. per cc. was used in correcting for the attraction of material between the station and sea level. This is consistent with the practice followed by the Dominion Observatory and is close to the density of Devonian and Carboniferous rocks in this area. If H is the elevation of the station in feet above sea level, the simple Bouguer anomaly is given by the expression:

$$g = g_{observed} - \gamma + 0.060H$$

Time did not permit the application of terrain corrections to the measurements. This type of correction is, of course, desirable for a full interpretation of any mountainous region. However, Garland and Tanner (1954) have made terrain corrections to 53 of the stations used in this map area. An examination of these corrections shows that they are small and uniform over the

area of the trench. An understanding of this uniformity can be gained from a study of the physiography of the area (Figure 1a). Nearly all the measurements were taken in the wide, fairly level, depression making up the Trench. Nearly all the stations have an elevation within the range between 2500 and 3500 feet. The Purcell range has an average elevation of 5000 feet with occasional peaks rising to 7000 feet above sea level. The mountains merge gradually into the trench but isolated peaks such as Mt. Baker do occur on the edge. The Rocky Mountains rise in an abrupt wall 6000 to 8000 feet above sea level. South of Cranbrook the Trench is generally 8 to 14 miles wide. The gravitational attraction of the Rocky Mountain mass is very nearly the same on most of the stations in this wide depression. This is best illustrated in Table IIIa summarizing the terrain correction made by Garland and Tanner.

TABLE IIIa. Terrain Corrections in Cranbrook-Elko Area

Region	Terrain Correction (milligals)	Average Correction (milligals)	Number of Stations
Rocky Mountain Trench	0.5 - 1.5		26
	1.6 - 2.5		9
	2.6 - 3.5		6
		1.4	(41)
Purcell Mountains	1.5 - 3.8	2.7	7
Rocky Mountains	3.4 - 9.3	6.0	5

The conclusion is reached that the effect of terrain is small and uniform along the Trench and the valley of the St. Mary River. It is, therefore, possible to treat the terrain effects as part of the regional gradient in the interpretation of the gravity anomalies.

3.3 Density of the Rocks

Garland and Tanner found a density difference of 0.7 gms. per cc. between the unconsolidated material along the Columbia River and bedrock. This high value can only apply to surficial deposits and would be expected to decrease as the fill was buried deeply. If the St. Eugene silts are Miocene as concluded by Berry, there is a good chance of other Tertiary deposits in the trench. The density difference between the Tertiary deposits and Palaeozoic or Precambrian bedrock might be expected to be as low as 0.3 or 0.4 gm. per cc. Since there are no measurements of density within the trench, a value of 0.5 gms. per cc. will be used in the interpretation of anomalies within the Trench. The calculated depth to bedrock is inversely proportional to the density difference so a reasonable estimate of the accuracy can be made.

Deposits of gypsum occur in the Devonian Burnais formation. Garland and Tanner have found their density to be 2.26 gm. per cc. These deposits occur along the

Dibble Creek fault and along Bull River. These features would be expected to show up as narrow bands of negative gravity anomalies.

Small intrusive bodies with compositions ranging from granodiorite to syenite occur north of St. Mary River, at the mouth of Bull River and in Hughes Range. The density of this material is not known but there is a small positive anomaly over the stock of altered monzonitic or granodioritic porphyry near the mouth of the Bull River.

Lastly, the region of the Moyie Lenia fault will be considered. The nature of the fault is not too important to gravity interpretation as the formations on both sides are similar and would have a similar density. However, the Moyie intrusives formed dense sills in the Aldridge formation and several lava flows occur near the top of the Siyeh formation. These might be expected to provide sufficient density contrast to delineate the fault zone. The Purcell lavas vary in composition from an andesite to a diabase. On Mt. Baker they vary in thickness from 50 to 300 feet and each flow is separated by 50 to 400 feet of sediment (Schofield, 1915). Garland (1954) finds the mean density of the Lower Purcell series to be 2.74 gm. per cc. A sample of amygdaloidal lava near Skookumchuck had a density of 2.84. Reich found

diabase extrusives to have densities varying from 2.73 to 3.12. A density difference of 0.10 gms. per cc. between the sediments and the extrusion is probably close to the true value.

The Moyie intrusives vary in thickness from 2 to over 2000 feet. Schofield refers to these as the Purcell sills and Rice calls them the Purcell intrusives. Their composition varies from a gabbro to a quartz diorite to granite. The densities of two typical sections was determined by Schofield (1915) and is reproduced in Table IVa. By weighting each density measurement according to the thickness the mean density of the gabbro is found to be 2.99 gms. per cc. and the mean density of the granite is 2.75. The mean weighted density of the 3820 foot column at Kingsgate is 2.89 gms. per cc. and the mean weighted density of the 5226 foot column at St. Mary Lake is 2.93 gm. per cc. It would seem that there is a density excess of about 0.20 gms. per cc. between a purely sedimentary sequence and one intruded with Moyie sills.

3.4 Accuracy of the Data

The simple Bouguer anomalies are believed to be accurate within 0.2 milligals for all stations located at benchmarks or surveyed points along highways and railroads. The effect of location errors are negligible

Table IVa. Densities of Two Columnar Sections in the Purcell Range

(after Schofield, 1915)

Formation	Rock Type	Thickness (feet)	Average Density (gm/cc.)
1. Moyie Sill on Mountain west of Kinsgate			
Aldridge	quartzite	200	2.76
Moyie Sill A	gabbro	26	2.96
	granite	80	2.76
	gabbro	29	2.97
Aldridge	quartzite	100	2.766
Movie Sill B	gabbro	30	2.93
Aldridge	quartzite	670	2.76
Moyie Sill C	granite	200	2.74
	intermediate	87	2.76
	gabbro	623	3.00
Aldridge	quartzite	75	2.76
Moyie Sill D	gabbro	1500	2.99
Aldridge	quartzite	200	2.76
	Total Thickness	3820	
2. St. Mary Sills on Mountain 10 miles west of Marysville			
Aldridge	quartzite		
Sill A	granite	70	2.76
	gabbro & intermediate	70	2.89
Aldridge	quartzite, argillaceous	400	
Sill B	gabbro (hornblende)	985	2.99
Aldridge	quartzite, argillaceous	200	
Sill C	gabbro, hornblende	123	2.99
Aldridge	quartzite	300±	
Sill D	gabbro	565	2.99
Aldridge	quartzite	350±	
Sill E	gabbro	2163	2.99
	Total thickness	5226	

as a mistake of 1000 feet in latitude must be made to introduce 0.1 milligals error in the gravity value. The precision of stations for which the elevations were obtained by aneroid barometer is $\pm$ 0.6 milligals except for stations 47 to 58 which are in doubt by $\pm$ 2.1 milligals.

4. INTERPRETATION OF GRAVITY ANOMALIES

4.1 Anomalies Due to Overburden

Gravity methods are very effective in determining the thickness of unconsolidated material filling a basin around which bedrock outcrops. While the exact shape and depth to bedrock is indeterminate, the approximate result is often enough to determine the origin of the basin, be it glacial erosion or normal faulting or some other mechanism. The interpretation can proceed in a straightforward manner because one face of the body producing the anomaly, that is the surface, is completely determined. The density contrast between the fill and bedrock is so large that small irregularities in the densities do not affect the overall conclusion. The results of two investigations of similar anomalies in Nevada and California have recently been published (Thompson and Sandberg, 1958; Pakiser et al, 1960).

In many geologic situations, the horizontal dimensions of the density discontinuities are several times

the vertical dimensions. In such a case, the thickness of the body can be approximated by the Bouguer expression for an infinite plate.

$$\Delta g = 2\pi k \sigma H \tag{1}$$

k = the gravitational constant

σ = density

H = thickness of the plate

If the density difference between bedrock and fill is 0.5 gms. per cc. the thickness of the deposit in feet is approximately:

$$H = 157 \Delta g \tag{2}$$

Because the body has finite horizontal dimensions, the depth will be slightly underestimated.

If the gravity anomaly is roughly circular the body can be approximated by one or more cylinders. The gravity anomaly at the center of the cylinder can be found exactly (Heiland, 1940, p. 147). The approximate size and thickness of the cylinders can be obtained from an application of the Bouguer expression (2). The gravity anomaly of a surface distribution of mass is proportional to the solid angle subtended by the surface distribution at the station in question. Nettleton (1942) has tabulated the solid angles subtended by

circular laminar discs. The mass of the cylinder is then considered to be condensed upon the median plane and the gravity anomaly obtained from the tabulated solid angles. It is then possible to calculate the approximate anomaly at stations off the origin.

An examination of the Bouguer map reveals three large negative anomalies (Figure 2a, in pocket). The amplitude of the anomalies decrease to the northwest. The largest and southern-most anomaly is the Waldo gravity minimum (Figure 3a). North of the Waldo minimum is a small positive anomaly centered at Elko. It is underlain, in part, by the Dutch Creek formation around Elko, and in part, by intrusives outcropping at Sheep Mountain. This high represents the higher density of the Purcell series (2.74 gms. per cc.) as compared to the density used in making the Bouguer correction (2.67). From longitudinal and transverse cross sections of the Bouguer anomalies, the regional gradient can be estimated. This regional gradient is due, in part, to terrain effects, and in part, to deep seated density variations (isostatic compensation) which are not of interest here. The residual anomaly, relative to outcrops of bedrock, amounts to -19 milligals on this southern-most minimum. If the density difference between fill and bedrock is -0.5 gms. per cc., then the thickness

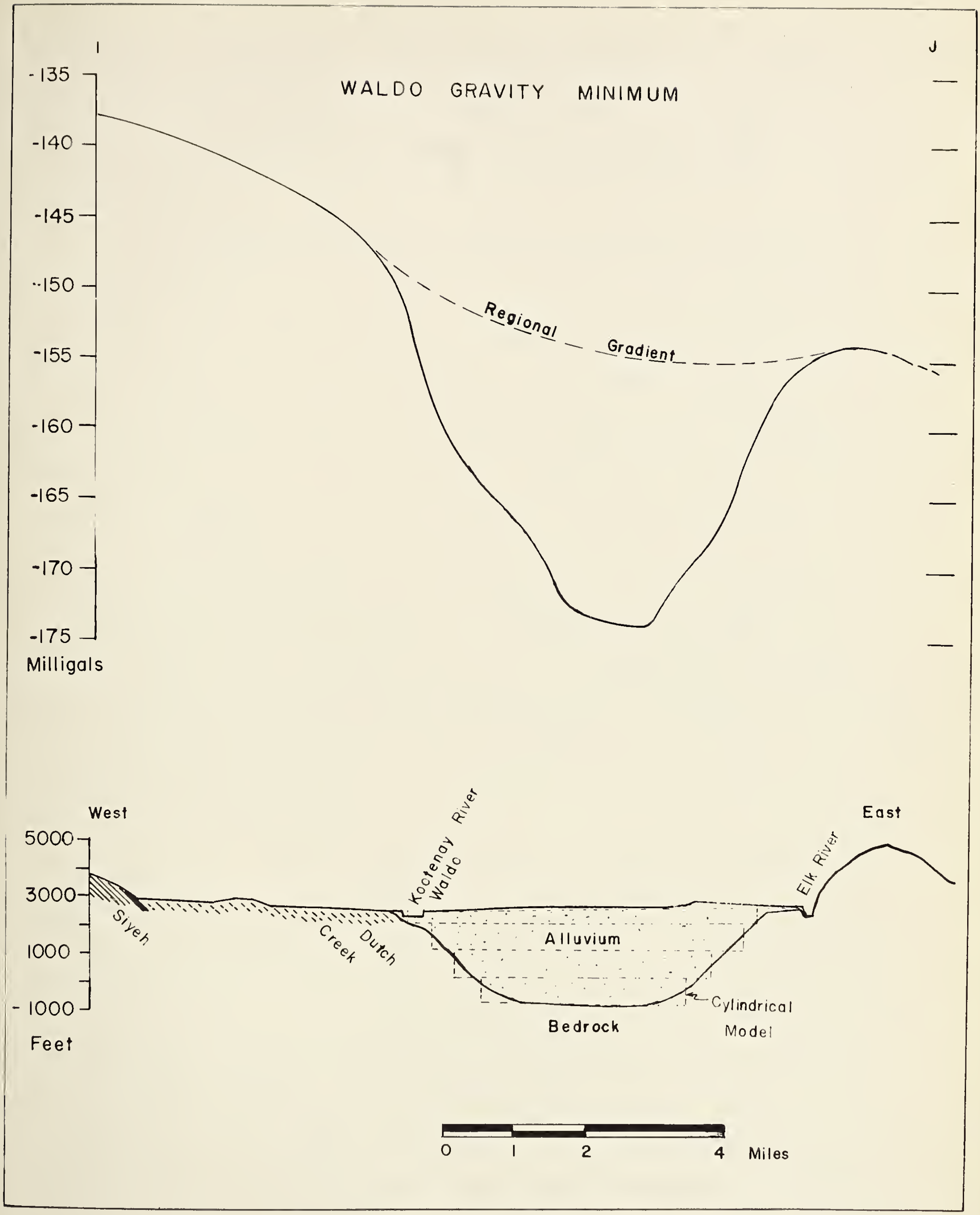


Figure 3a. Gravity profile and Geologic Section across the Rocky Mountain Trench at Waldo. The locations of the profiles are shown on figure 2a. The horizontal scale is twice the vertical scale.

of fill is 3500 feet. The density difference is thought to have a precision of ± 0.1 gms. per cc. The calculated depth may be as great as 4400 feet or as small as 2900 feet.

The fourteen milligal gravity minimum at Jaffray (Figure 4a) is in the shape of a square, three miles to a side. The depth of fill is calculated to be 2300 feet. From scattered outcrops to the north and east of this anomaly Leech (1958) maps a west dipping fault on the east wall of the Trench. There is a large gravity gradient which confirms the presence of this fault. The area north of this fault is particularly interesting as it consists of a Palaeozoic sequence that rises 2200 feet above the level of the trench floor. It is entirely broken up by faulting and is evidently a small horst adjacent to the graben making up the Jaffray gravity minimum.

The Fort Steele gravity minimum (Figure 4a) has eight milligals of closure. It is rectangular in shape with dimensions three by four miles. The calculated depth of fill is 1400 feet. The northern edge is complicated by the presence of the Boulder Creek fault. This fault appears to be a thrust with the Aldridge formation on the north and the Creston and Kitchener formations on the south but there may be a strike-

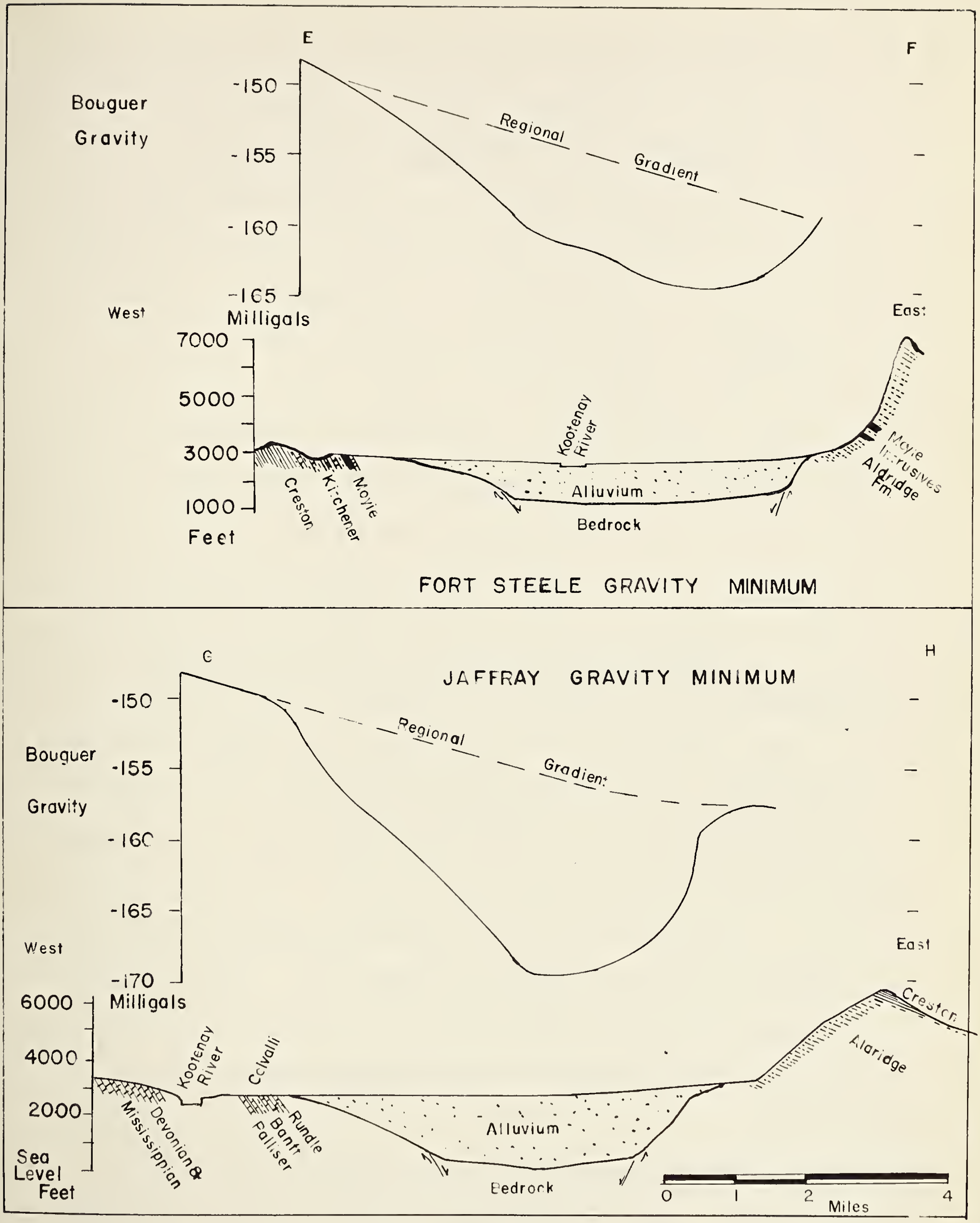


Figure 4a. Gravity Profile and Geologic Section across the Rocky Mountain Trench at Fort Steele and Jaffray. The locations of the profiles are shown in figure 2a. The horizontal scale is twice the vertical scale.

slip component to the motion. The dip of the fault is very nearly vertical or steeply northward and it brings together blocks with a complicated history (Leech, 1958). This fault may extend to the St. Mary fault in the Purcell Mountains but more gravity measurements are necessary to establish this correlation.

North of Fort Steele the bedrock must be beneath a thin cover of till. There is a suggestion of a fourth minimum four miles north of Fort Steele. The Dibble Creek fault, which has gypsum in the footwall, may extend into the trench and widen the southern end of the Fort Steele minimum.

4.2 Anomalies Related to Faults and Intrusives

Various small anomalies are apparent on the Bouguer map which appear related to structural features. The density of the data is not sufficient to make quantitative calculations but a qualitative discussion may stimulate further research. Any gravity study which is to be successful depends critically on a prior detailed geologic study. The density contrast between till or alluvium and bedrock is so great that gravity anomalies due to the recent deposits may entirely obscure more fundamental trends.

The stock of monzonitic or granodioritic porphyry at Bull River appears to cause a one milligal gravity high. Intrusives

on Sheep Mountain south of Elko appear to cause an anomaly of similar magnitude. The composition of the intrusives on Sheep Mountain is not known. If this correlation is correct the bulk of the intrusive must have a composition which corresponds to the "grey granodioritic" phase of Rice (1947). This phase has very little potash feldspar but about 14 per cent of ferromagnesian minerals. The density excess over the surrounding Palaeozoic rocks can scarcely be much more than 0.05 gms. per cc.

The low trend along Bull River to Lime Creek is probably due to gypsum which has a density of 2.26 gms. per cc. Further north the anomaly becomes positive so the deposit of gypsum may follow Lime Creek as inferred by Leech (1958) from the presence of sinkholes. The gravity anomaly between stations 31 and 81 may be an extension of this gypsiferous formation along the west dipping fault mentioned in connection with the Jaffray minimum.

4.3 The Moyie Lenia Fault

A linear gravity minimum trends along the Moyie Lenia fault south of Cranbrook to Moyie Lake (Figure 2a, in pocket). This minimum does not appear to be related to low density fill because several low values are near bedrock. The Purcell sediments on both sides of the fault have nearly the same density so they could not materially affect the gravitational field. It is proposed that the Moyie sills are responsible for the minimum trend. The sills of predominantly basic material have intruded the Aldridge formation. The density relations have already been reviewed in section 3.3.

Figure 5a illustrates the gravity anomaly across the Moyie Lenia fault. Below it is a cross section showing two solutions which produce a similar gravitational field. The theoretical gravity produced by the Moyie sills and Purcell extrusions has been calculated with the aid of a two dimensional graticule chart (Nettleton, 1940). More elaborate computations are scarcely warranted until more complete geologic and geophysical data is available. The Moyie Lenia fault presents one of those unusual situations in which a density excess produces a negative gravity anomaly. A closer fit between the observed and theoretical gravity could be made by altering the thickness and dip of the Moyie intrusives and by adding a small

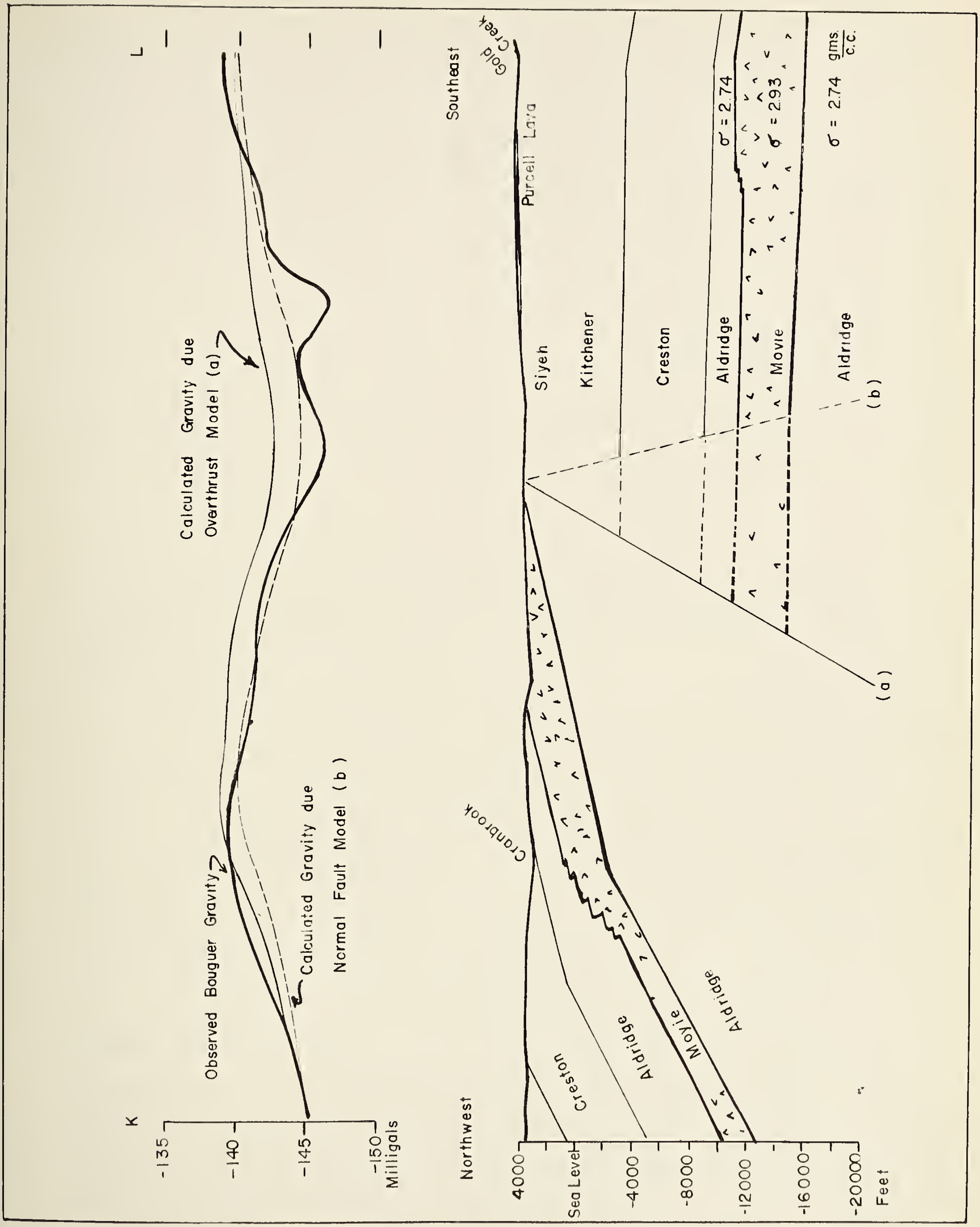


Figure 5a. Gravity Profile and Geologic Section across the Moyie Lenia Fault in the Purcell Mountains. The location of the profile is shown in figure 2a. The horizontal and vertical scales are equal. Two possible interpretations are illustrated together with the resultant gravity anomaly.

amount of fill. Intense shearing of the rock along the fault plane may have decreased the density. On Peavine Creek the Aldridge sediments and sills are converted from massive rocks to closely cleaved, fissile phyllitic rocks in many places. (Leech, written communication). Much of the area is blanketed with a heavy cover of timber and outcrops are obscurred by recent deposits so the thickness of the section containing the sills is not known. In the theoretical cross section it is shown to increase in thickness from 2000 to 5000 feet towards the southeast. The interpretation is not changed significantly if the single sill shown in the diagram is actually composed of numerous basaltic flows separated by sediment.

The Purcell extrusives on top of the Siyeh formation contribute a small positive anomaly on the southeast block. These extensive lavas, mostly dipping 20° to 30° northeasterly, may total about 1000 feet in thickness. The section is repeated by faults, most of which appear to be steep and to strike northwesterly. As a result the plan widths of lava are anomalously great (written communication, Leech). It is difficult to calculate the net effect of these lavas without more exact geologic data but they would be expected to produce a positive anomaly of one or two milligals.

The normal fault solution produces a better fit but this solution is not unique and a slight redistribution of the mass in the overthrust case would also produce fair agreement. Kirkham (1930) reviewed all the data on this fault and concluded that it was an overthrust with a steep fault plane that dips west. The fault plane forms an arc, concave to the east, and runs for 118 miles through British Columbia, Idaho and Montana. Daly (1910) believed the fault to be normal at the International Boundary. Schofield (1915) states:

> The second great movement which affected the Purcell Range was normal faulting, a northeast-southwest system, including the Marysville and Moyie faults and several small faults of lesser importance; and a northwest-southeast system, the chief one being the Cranbrook fault.

However, his structure diagram (AB, Map 147A) shows the Moyie fault to be overthrust. The problem has not been resolved in this study but it appears that a detailed gravitational and magnetic survey along the entire length of the break may ultimately provide enough data to decide if the fault is normal, reverse, or possibly strike-slip.

The relative low along the Moyie Lenia fault diminishes as the trench is approached. This is readily understandable as the east limb of the Purcell geanticline dips steeply to the east along the trench. The Siyeh

formation outcrops near Rampart and this indicates that the Moyie intrusives in the northwest fault block have been buried too deeply to cause a detectable gravity anomaly. It is doubtful if a direct connection can be shown between the Moyie Lenia and the Dibble Creek fault by gravity methods.

5. CONCLUSIONS

Gravity measurements indicate the presence of three deep basins, now filled with unconsolidated material, along the Trench between Fort Steele and the International Boundary. From north to south the depth of the basins are 1400 feet (Fort Steele minimum), 2300 feet (Jaffray minimum), and 3500 feet (Waldo minimum) with the limits being about -17% to +25%. The basins are thought to represent down-faulted blocks along longitudinal and transverse faults along the trench. Between the Jaffray and Fort Steele minimum there is 2200 feet of topographic relief with Palaeozoic outcrops which indicate that this is a small horst. Leech(1959) has observed that "South of latitude 49° 30', the Trench seems due fundamentally to block faulting and lacks important strike-slip displacements." The gravity data confirms this observation and provides evidence that the amplitude of

block faulting decreases as one proceeds northward from the International Boundary towards Fort Steele.

This investigation has indicated an economic significance to the use of gravity in this area. Stocks of monzonitic or granodioritic porphyry appear to cause one-milligal gravity highs. There is, therefore, a possibility of mapping extensions to the outcrops with a very accurate and detailed gravity survey. Many of the sulfide deposits in this area occur in Aldridge strata. Because of the presence of dense Moyie sills the appearance of the Aldridge formation is accompanied by a positive gravity anomaly. This is illustrated between Marysville and Kimberley, north of Fort Steele and near Cranbrook. Of more direct application is the use of gravity to determine the trend and importance of gypsum deposits which are used in the cement industry.

A linear gravity minimum has been found along the Moyie Lenia fault. This trend is really composed of two high anomalies, one on each side of the fault, which are caused by dense sills of basaltic material. This fault can be treated as a steeply dipping overthrust in which the northwest block moved upward relative to the southeast block or as a normal fault with the northwest block moving upwards relative to the southeast block. Of the two interpretations presented the normal

fault solution fits the observed gravity data slightly better. It does not seem possible to tie the Dibble Creek fault to the Moyie Lenia fault on gravity data alone but the Dibble Creek fault appears to extend into the trench to within three miles of Rampart. Similarly the Boulder Creek fault would seem to extend into the Trench past Fort Steele. More observations are necessary to check its connection to the St. Mary fault system as postulated by Rice (1937).

BIBLIOGRAPHY

BIBLIOGRAPHY

Berry, E. W., 1929. The Age of the St. Eugene Silts in the Kootenay Valley, British Columbia. Trans. Royal Soc. Canada, ser. IV, pp. 47-48.

Daly, R. A., 1912. Geology of the North American Cordillera at the Forty-ninth Parallel. Geological Survey of Canada, Memoir 32, Part III, Sheet 5, Moyie Range.

Garland, G. D. and Tanner, J. G., 1957. Investigations of Gravity and Isostasy in the Southern Canadian Cordillera. Publications of the Dominion Observatory, Ottawa. Vol. XIX, No. 5.

Heiland, C. A., 1940. Geophysical Exploration. Prentice-Hall, New York.

Hollick, A., 1927. The Flora of the St. Eugene Silts, Kootenay Valley, British Columbia. Memoir, New York Botanical Garden 7, pp. 389-464.

Kirkham, V. R. D., 1930. The Moyie Lenia Overthrust Fault. Journal of Geology, Vol. 38, No. 4, pp. 364-374.

Leech, G. B., 1958. Fernie Map-Area, West Half, British Columbia. Geological Survey of Canada Paper 58-10.

________, 1959. The Southern Part of the Rocky Mountain Trench. The Canadian Mining and Metallurgical Bulletin, May, pp. 10-16.

Nettleton, L. L., 1942. Gravity and Magnetic Calculations. Geophysics, Vol. 7, pp. 293-310.

________, 1940. Geophysical Prospecting for Oil. McGraw-Hill Book Company, Inc. New York.

North, F. K., and Henderson, G. G. L., 1954. The Rocky Mountain Trench. Guide Book Alberta Society of Petroleum Geologists. pp. 82-100.

Pakiser, L. C., Press, F., and Kane, M. F., 1960. Geophysical Investigation of Mono Basin, California. Bulletin of the Geological Society of America, Vol. 71, pp. 415-448.

Reich, H., 1930. Handbuch der Experimental Physik. Vol. XXV, pt. 3, p. 16.

Rice, H. M. A., 1937. Cranbrook Map-Area, British Columbia. Geological Survey of Canada Memoir 207.

________, 1947. Geology and mineral deposits of the Princeton Map-Area, British Columbia. Geological Survey of Canada Memoir 243.

Schofield, S. J., 1915. Cranbrook Map Area, British Columbia. Geological Survey of Canada Memoir 76.

Thompson, G. A. and Sandberg, C. H., 1958. Structural Significance of Gravity Surveys in the Virginia City-Mount Rose Area, Nevada and California. Bulletin of the Geological Society of America, Vol. 69, pp. 1269-1282.

APPENDIX

APPENDIX I. TABLE II.

PRINCIPAL FACTS FOR GRAVITY STATIONS

ATHABASKA GLACIER

No.	Station	Longitude		Latitude			Elevation	Observed Gravity	Free Air Anomaly	Simple Bouguer Anomaly	Terrain Correction (A - I)	Bouguer Anomaly
		°	'	°	'	"	feet	milligals	milligals	milligals	milligals	milligals
1	A 1	117	15.6	52	10	49	7773	980,606.00	65.94	-198.79	11.7	-187.1
2	A 2	117	15.7	52	10	50	7777	980,604.78	65.07	-199.79	11.5	-188.3
3	A 3	117	15.7	52	10	51	7785	980,603.50	64.51	-200.62	11.5	-189.1
4	A 4	117	15.8	52	10	53	7785	980,602.42	63.38	-201.75	10.3	-191.4
5	A 5	117	15.9	52	10	54	7777	980,602.94	63.13	-201.73	9.4	-192.3
6	A 6	117	16.0	52	10	56	7767	980,603.36	62.56	-201.96	9.3	-192.7
7	A 7	117	16.0	52	10	57	7761	980,603.92	62.54	-201.78	9.4	-192.4
8	B 1	117	15.4	52	11	03	7441	980,620.33	48.70	-204.75	13.1	-191.6
9	B 2	117	15.5	52	11	04	7431	980,620.16	47.57	-205.54	12.1	-193.4
10	B 3	117	15.6	52	11	06	7432	980,619.66	47.11	-206.04	10.9	-195.1
11	B 4	117	15.6	52	11	07	7446	980,618.57	47.31	-206.31	10.3	-196.0
12	B 5	117	15.7	52	11	08	7453	980,618.01	47.39	-206.47	9.9	-196.6
13	B 6	117	15.7	52	11	10	7459	980,617.77	47.66	-206.41	9.5	-196.9
14	B 7	117	15.8	52	11	12	7460	980,618.11	48.05	-206.05	9.4	-196.6
15	B 8	117	15.9	52	11	13	7454	980,618.96	48.31	-205.58	9.4	-196.2
16	B 9	117	16.0	52	11	16	7435	980,620.81	48.29	-204.96	10.3	-194.7
17	B 10	117	16.1	52	11	14	7487	980,621.15	53.50	-201.48	12.4	-189.1
18	C 1	117	15.0	52	11	16	7356	980,628.11	48.16	-202.36	13.8	-188.6

TABLE II - PRINCIPAL FACTS FOR GRAVITY STATIONS

ATHABASKA GLACIER

No.	Station	Longitude		Latitude			Elevation	Observed Gravity	Free Air Anomaly	Simple Bouguer Anomaly	Terrain Correction (A-I)	Bouguer Anomaly
		°	'	°	'	"	feet	milligals	milligals	milligals	milligals	milligals
19	C 2	117	15.1	52	11	17	7336	980,628.03	48.18	-203.66	12.4	-191.3
20	C 3	117	15.2	52	11	18	7318	980,627.94	44.38	-204.85	10.9	-193.9
21	C 4	117	15.2	52	11	19	7332	980,626.49	44.22	-205.49	10.3	-195.2
22	C 5	117	15.3	52	11	21	7337	980,625.32	43.47	-206.41	9.8	-196.6
23	C 6	117	15.4	52	11	22	7341	980,625.01	43.51	-206.50	9.3	-197.2
24	C 7	117	15.4	52	11	23	7347	980,624.68	43.49	-206.73	8.9	-197.8
25	C 8	117	15.5	52	11	24	7346	980,624.74	43.67	-206.52	8.6	-197.9
26	C 9	117	15.5	52	11	25	7352	980,624.66	44.13	-206.25	8.6	-197.6
27	C 10	117	15.7	52	11	27	7352	980,624.95	44.37	-206.02	8.6	-197.4
28	C 11	117	15.6	52	11	28	7348	980,625.97	44.98	-205.27	8.6	-196.7
29	C 12	117	15.7	52	11	29	7346	980,627.39	46.19	-203.99	8.6	-195.4
30	C 13	117	15.8	52	11	30	7345	980,628.50	47.18	-202.97	9.0	-194.0
31	C 14	117	15.9	52	11	32	7339	980,630.48	48.55	-201.39	10.1	-191.3
32	C 14½	117	15.9	52	11	33	7371	980,629.84	50.89	-200.14	11.0	-189.1
33	C 16	117	15.9	52	11	35	7462	980,626.88	56.44	-197.69	12.7	-185.0
34	D 1	117	14.8	52	11	32	7261	980,636.32	47.06	-200.23	10.6	-189.6
35	D 2	117	14.9	52	11	33	7218	980,637.26	43.92	-201.90	10.3	-191.6
36	D 3	117	14.9	52	11	34	7241	980,634.80	43.51	-203.06	9.3	-193.8

TABLE II - PRINCIPAL FACTS FOR GRAVITY STATIONS

ATHABASKA GLACIER

No.	Station	Longitude		Latitude			Elevation	Observed Gravity	Free Air Anomaly	Simple Bouguer Anomaly	Terrain Correction (A-I)	Bouguer Anomaly
		°	'	°	'	"	feet	milligals	milligals	milligals	milligals	milligals
37	D 4	117	15.0	52	11	36	7245	980,633.65	42.78	-203.96	8.7	-195.3
38	D 5	117	15.1	52	11	38	7250	980,632.84	42.39	-204.52	8.0	-196.5
39	D 6	117	15.2	52	11	40	7249	980,632.96	42.37	-204.51	7.4	-197.1
40	D 7	117	15.2	52	11	41	7249	980,633.23	42.62	-204.26	7.1	-197.2
41	D 8	117	15.3	52	11	41	7250	980,633.32	42.80	-204.11	7.2	-196.9
42	D 9	117	15.3	52	11	43	7249	980,634.30	43.64	-203.24	7.5	-195.7
43	D 10	117	15.4	52	11	44	7252	980,635.12	44.71	-202.27	7.6	-194.7
44	D 11	117	15.5	52	11	47	7260	980,636.44	46.71	-200.54	8.3	-192.2
45	D 11½	117	15.6	52	11	48	7287	980,637.12	49.91	-198.26	9.0	-189.3
46	E 0	117	14.4	52	11	47	7128	980,648.50	46.36	-196.40	10.6	-185.8
47	E 1	117	14.5	52	11	48	7127	980,647.52	45.26	-197.46	10.3	-187.2
48	E 2	117	14.5	52	11	49	7096	980,648.35	43.15	-198.51	9.8	-188.7
49	E 3	117	14.6	52	11	52	7119	980,645.86	42.75	-199.70	8.6	-191.1
50	E 4	117	14.7	52	11	54	7124	980,645.15	42.46	-200.16	7.6	-192.6
51	E 5	117	14.7	52	11	57	7127	980,645.09	42.61	-200.11	7.3	-192.8
52	E 6	117	14.8	52	11	59	7125	980,645.71	43.00	-199.66	7.1	-192.6
53	E 7	117	14.9	52	12	01	7121	980,646.76	43.62	-198.90	6.9	-192.0
54	E 8	117	15.0	52	12	04	7110	980,649.40	45.16	-197.07	6.9	-190.2

TABLE II - PRINCIPAL FACTS FOR GRAVITY STATIONS

ATHABASKA GLACIER

No.	Station		Longitude		Latitude			Elevation	Observed Gravity	Free Air Anomaly	Simple Bouguer Anomaly	Terrain Correction (A-I)	Bouguer Anomaly
			°	'	°	'	"	feet	milligals	milligals	milligals	milligals	milligals
55	E	9-C	117	15.0	52	12	07	7077	980,654.00	46.57	-194.45	7.4	-187.0
56	H	1	117	14.2	52	13	00	6955	980,661.17	42.44	-194.43	9.4	-185.0
57	H	2	117	14.2	52	12	02	6919	980,662.59	40.43	-195.21	8.7	-186.5
58	H	3	117	14.3	52	12	05	6952	980,659.47	40.33	-196.43	7.4	-189.0
59	H	4	117	14.4	52	12	08	6967	980,658.29	40.50	-196.78	6.7	-190.1
60	H	5	117	14.5	52	12	10	6974	980,657.91	40.72	-196.79	6.6	-190.2
61	H	6	117	14.6	52	12	11	6970	980,658.56	40.98	-196.40	6.4	-190.0
62	H	7	117	14.7	52	12	13	6963	980,659.54	41.25	-195.89	6.3	-189.6
63	H	8	117	14.7	52	12	15	6972	980,660.57	43.08	-194.37	6.4	-188.0
64	H	9	117	14.8	52	12	16	6996	980,660.71	45.44	-192.82	7.0	-185.8
65	F	0	117	14.0	52	12	08	6884	980,667.18	41.58	-192.87	8.8	-184.1
66	F	1	117	14.0	52	12	11	6845	980,669.93	40.59	-192.53	8.6	-183.9
67	F	2	117	14.1	52	12	13	6832	980,670.06	39.45	-193.23	7.8	-185.4
68	F	3	117	14.2	52	12	14	6849	980,668.71	39.67	-193.59	7.4	-186.2
69	F	4	117	14.2	52	12	16	6863	980,667.84	40.06	-193.67	7.0	-186.7
70	F	5	117	14.3	52	12	17	6876	980,666.99	40.42	-193.76	6.8	-187.0
71	F	6	117	14.4	52	12	19	6889	980,647.96	41.78	-193.44	6.7	-186.7
72	F	7	117	14.4	52	12	20	6884	980,666.76	40.87	-193.58	6.6	-187.0

TABLE II - PRINCIPAL FACTS FOR GRAVITY STATIONS

ATHABASKA GLACIER

No.	Station	Longitude		Latitude			Elevation	Observed Gravity	Free Air Anomaly	Simple Bouguer Anomaly	Terrain Correction (A-I)	Bouguer Anomaly
		°	'	°	'	"	feet	milligals	milligals	milligals	milligals	milligals
73	F 8	117	14.4	52	12	21	6883	980,666.90	40.88	-193.53	6.6	-186.9
74	F 9	117	14.6	52	12	23	6871	980,668.70	41.51	-192.50	6.9	-185.6
75	F 10	117	14.7	52	12	25	6846	980,672.95	43.36	-189.79	7.2	-182.6
76	G 1	117	13.9	52	12	29	6581	980,692.03	37.42	-186.71	8.7	-178.0
77	G 2	117	14.0	52	12	30	6603	980,690.87	38.30	-186.58	8.5	-178.1
78	G 3	117	14.0	52	12	32	6605	980,690.60	38.18	-186.77	8.2	-178.6
79	G 4	117	14.1	52	12	34	6601	980,691.38	38.53	-186.28	7.9	-178.4
80	G 5	117	14.2	52	12	36	6601	980,691.53	38.63	-186.18	8.0	-178.2
81	G 6	117	14.2	52	12	37	6588	980,692.20	38.05	-186.32	7.8	-178.5
82	G 7	117	14.3	52	12	39	6546	980,694.52	36.38	-186.56	8.0	-178.6
83	G 8	117	14.4	52	12	43	6565	980,692.80	36.34	-187.24	8.5	-178.7
84	L 1	117	15.9	52	10	48	7793	980,602.19	64.04	-201.37	10.3	-191.1
85	L 2	117	15.9	52	10	52	7796	980,602.69	64.72	-200.79	9.6	-191.2
86	L 10	117	15.8	52	11	04	7506	980,616.05	50.51	-205.12	9.8	-195.3
87	L 11	117	15.8	52	11	07	7484	980,616.80	49.11	-205.77	9.5	-196.3
88	L 12	117	15.8	52	11	09	7467	980,617.37	48.04	-206.30	9.6	-196.7
89	L 13	117	15.7	52	11	12	7450	980,618.28	47.27	-206.48	9.2	-197.3
90	L 14	117	15.7	52	11	15	7433	980,619.31	46.64	-206.54	8.9	-197.6

TABLE II - PRINCIPAL FACTS FOR GRAVITY STATIONS

ATHABASKA GLACIER

No.	Station	Longitude		Latitude			Elevation	Observed Gravity	Free Air Anomaly	Simple Bouguer Anomaly	Terrain Correction (A-I)	Bouguer Anomaly
		°	'	°	'	"	feet	milligals	milligals	milligals	milligals	milligals
91	L 15	117	15.7	52	11	18	7415	980,620.51	46.07	-206.50	8.8	-197.7
92	L 16	117	15.6	52	11	22	7385	980,622.51	45.15	-206.40	9.0	-197.4
93	L 18	117	15.4	52	11	29	7314	980,627.29	43.08	-206.01	8.5	-197.5
94	L 19	117	15.4	52	11	33	7284	980,628.87	41.74	-206.33	8.0	-198.3
95	L 20	117	15.3	52	11	37	7265	980,631.47	42.45	-204.97	7.5	-197.5
96	L 22	117	15.1	52	11	45	7234	980,635.16	43.04	-203.33	6.9	-196.4
97	L 23	117	15.0	52	11	49	7212	980,637.43	43.14	-202.48	6.7	-195.8
98	L 24	117	15.0	52	11	53	7187	980,639.65	42.92	-201.85	6.8	-195.0
99	L 25	117	14.9	52	11	56	7157	980,642.75	43.12	-200.63	6.8	-193.8
100	L 26	117	14.9	52	11	59	7143	980,644.33	43.31	-199.96	7.0	-193.0
101	L 27	117	14.8	52	12	00	7120	980,646.41	43.20	-199.29	7.1	-192.2
102	L 28	117	14.8	52	12	03	7085	980,649.23	42.65	-198.64	7.0	-191.6
103	L 29	117	14.7	52	12	07	7032	980,653.55	41.89	-197.60	6.8	-190.8
104	L 31	117	14.5	52	12	17	6920	980,662.97	40.53	-195.14	6.4	-188.7
105	L 33	117	14.4	52	12	22	6857	980,669.55	41.07	-192.45	6.9	-185.5
106	L 34	117	14.3	52	12	25	6817	980,673.58	41.27	-190.90	7.0	-183.9
107	L 35	117	14.3	52	12	27	6774	980,677.02	40.61	-190.09	7.2	-182.9
108	L 36	117	14.2	52	12	33	6673	980,685.72	39.66	-187.60	7.5	-180.1

TABLE II - PRINCIPAL FACTS FOR GRAVITY STATIONS

ATHABASKA GLACIER

No.	Station	Longitude		Latitude			Elevation	Observed Gravity	Free Air Anomaly	Simple Bouguer Anomaly	Terrain Correction (A-I)	Bouguer Anomaly
		°	'	°	'	"	feet	milligals	milligals	milligals	milligals	milligals
109	Lake	117	14.1	52	12	45	6317	980,709.54	29.71	-185.43	9.7	-175.7
110	Bridge	117	14.0	52	12	48	6330	980,709.06	30.38	-185.20	9.7	-175.5
111	M 13	117	16.1	52	11	20	7422	980,623.97	50.14	-202.63	12.2	-190.4
112	M 14	117	16.0	52	11	25	7412	980,625.65	50.76	-201.67	12.0	-189.7
113	M 18	117	15.7	52	11	34	7314	980,630.45	46.12	-202.97	8.5	-194.5
114	M 19	117	15.6	52	11	38	7290	980,632.26	45.59	-202.70	8.1	-194.6
115	M 23	117	15.4	52	11	55	7266	980,641.16	51.81	-195.65	8.5	-187.1
116	M 24	117	15.3	52	12	00	7202	980,645.70	50.20	-195.08	8.6	-186.5
117	M 28	117	14.9	52	12	11	7031	980,657.57	45.72	-193.73	7.6	-186.1
118	M 31	117	14.7	52	12	18	6957	980,662.81	43.83	-193.10	6.6	-186.5
119	M 35	117	14.6	52	12	31	6788	980,677.49	42.30	-188.88	7.5	-181.4
120	Gravel	117	15.4	52	10	57	7676	980,612.01	62.63	-198.79	14.9	-183.9
121	B	117	15.3	52	11	11	7372	980,624.02	45.71	-205.36	12.4	-193.0
122	D	117	15.0	52	11	21	7337	980,629.73	47.88	-202.00	11.4	-190.6
123	E	117	14.9	52	11	28	7276	980,634.24	46.48	-201.32	11.5	-189.8
124	G	117	14.6	52	11	42	7189	980,642.33	46.06	-198.77	10.0	-188.8
125	H	117	14.3	52	11	55	7031	980,655.29	43.83	-195.62	9.6	-186.0
126	Hydro #1	117	13.5	52	13	12	6468	980,703.79	37.50	-182.78		
127	Gate-house	117	12.3	52	12	50	6583	980,696.7(0)	41.77	-182.43	(8.7)	(173.7)

APPENDIX 2 - TABLE III

RRAIN CORRECTIONS FOR HAYFORD ZONES B TO J ON THE ATHABASKA GLACIER

Units of Milligals

No.	Station	B	C	D	E	F	G	H	I	J	Total
1	A 1	0.16	0.19	1.11	3.57	3.65	1.76	0.76	0.35	0.19	11.74
2	A 2	0.20	0.18	0.83	3.50	3.70	1.80	0.80	0.34	0.18	11.53
3	A 3	0.20	0.19	0.65	3.44	3.81	1.90	0.83	0.33	0.18	11.53
4	A 4	0.20	0.19	0.37	2.56	3.65	1.98	0.87	0.32	0.18	10.32
5	A 5	0.24	0.18	0.30	1.69	3.51	2.05	0.92	0.32	0.18	9.39
6	A 6	0.20	0.16	0.28	1.55	3.53	2.10	0.95	0.32	0.18	9.27
7	A 7	0.21	0.15	0.30	1.42	3.56	2.26	0.97	0.31	0.18	9.36
8	B 1	0.15	0.26	1.04	3.06	4.54	2.32	1.05	0.49	0.23	13.14
9	B 2	0.00	0.15	0.95	2.51	4.41	2.33	1.07	0.48	0.23	12.13
10	B 3	0.00	0.08	0.45	1.96	4.28	2.34	1.09	0.47	0.23	10.90
11	B 4	0.00	0.06	0.22	1.75	4.09	2.35	1.14	0.46	0.23	10.30
12	B 5	0.00	0.06	0.14	1.54	3.93	2.36	1.18	0.45	0.23	9.89
13	B 6	0.02	0.06	0.09	1.21	3.82	2.37	1.22	0.44	0.23	9.46
14	B 7	0.00	0.06	0.11	1.32	3.60	2.38	1.23	0.43	0.23	9.36
15	B 8	0.00	0.06	0.26	1.43	3.39	2.41	1.25	0.42	0.23	9.45
16	B 9	0.03	0.10	0.80	2.19	2.80	2.42	1.32	0.40	0.23	10.29
17	B 10	0.81	0.62	1.60	2.54	2.43	2.44	1.36	0.37	0.23	12.40
18	C 1	0.58	0.84	1.02	2.85	4.20	2.41	1.02	0.65	0.27	13.84
19	C 2	0.22	0.40	0.95	2.46	4.00	2.41	1.08	0.64	0.27	12.43
20	C 3	0.00	0.04	0.58	2.08	3.79	2.42	1.14	0.63	0.27	10.95
21	C 4	0.00	0.06	0.35	1.74	3.64	2.43	1.20	0.62	0.27	10.31
22	C 5	0.00	0.04	0.33	1.40	3.49	2.43	1.26	0.61	0.27	9.83
23	C 6	0.00	0.05	0.05	1.20	3.34	2.44	1.32	0.60	0.27	9.27
24	C 7	0.00	0.05	0.02	0.99	3.19	2.44	1.38	0.59	0.27	8.93
25	C 8	0.00	0.05	0.02	1.02	2.77	2.44	1.45	0.58	0.27	8.60
26	C 9	0.00	0.04	0.02	1.04	2.75	2.44	1.52	0.57	0.27	8.65
27	C 10	0.00	0.04	0.06	1.03	2.67	2.45	1.53	0.56	0.27	8.61
28	C 11	0.00	0.04	0.09	1.03	2.63	2.44	1.55	0.55	0.27	8.60
29	C 12	0.00	0.04	0.29	1.28	2.17	2.44	1.56	0.54	0.27	8.59
30	C 13	0.00	0.08	0.44	1.53	2.14	2.43	1.58	0.53	0.27	9.00

APPENDIX 2 - TABLE III

TERRAIN CORRECTIONS FOR HAYFORD ZONES B TO J ON THE ATHABASKA GLACIER

Units of Milligals

No.	Station	B	C	D	E	F	G	H	I	J	Total
31	C 14	0.02	0.17	1.30	1.85	1.95	2.43	1.59	0.52	0.27	10.10
32	C 14½	0.03	0.37	1.87	2.18	1.76	2.43	1.61	0.50	0.27	11.02
33	C 16	0.56	0.89	2.54	2.18	1.76	2.43	1.61	0.50	0.27	12.74
34	D 1	0.33	0.13	0.87	1.80	3.08	2.45	0.98	0.69	0.32	10.65
35	D 2	0.09	0.27	0.82	1.70	2.89	2.44	1.05	0.70	0.32	10.28
36	D 3	0.00	0.01	0.43	1.58	2.76	2.42	1.12	0.70	0.32	9.34
37	D 4	0.00	0.03	0.26	1.21	2.61	2.40	1.19	0.70	0.32	8.72
38	D 5	0.00	0.02	0.08	0.85	2.45	2.36	1.26	0.69	0.32	8.03
39	D 6	0.00	0.02	0.00	0.85	1.93	2.30	1.33	0.69	0.32	7.44
40	D 7	0.00	0.02	0.04	0.86	1.53	2.25	1.41	0.69	0.32	7.12
41	D 8	0.00	0.02	0.07	0.94	1.54	2.24	1.44	0.68	0.32	7.25
42	D 9	0.00	0.02	0.16	1.03	1.58	2.22	1.47	0.67	0.32	7.47
43	D 10	0.00	0.01	0.35	1.06	1.47	2.20	1.51	0.66	0.32	7.58
44	D 11	0.00	0.10	1.02	1.09	1.36	2.19	1.54	0.66	0.32	8.28
45	D 11½	0.03	0.63	1.78	0.84	1.04	2.17	1.58	0.65	0.32	9.04
46	E 0	0.23	0.16	0.86	1.96	2.45	2.53	1.29	0.72	0.37	10.57
47	E 1	0.10	0.27	0.75	2.00	2.32	2.45	1.29	0.75	0.37	10.30
48	E 2	0.13	0.09	0.57	2.04	2.19	2.36	1.29	0.78	0.37	9.82
49	E 3	0.08	0.10	0.26	1.33	2.13	2.27	1.29	0.81	0.37	8.64
50	E 4	0.08	0.08	0.07	0.62	2.08	2.18	1.30	0.84	0.37	7.62
51	E 5	0.12	0.08	0.09	0.50	1.86	2.09	1.30	0.87	0.37	7.28
52	E 6	0.14	0.09	0.10	0.68	1.39	2.03	1.38	0.88	0.38	7.07
53	E 7	0.10	0.14	0.09	0.67	1.26	1.96	1.40	0.90	0.38	6.90
54	E 8	0.00	0.13	0.28	0.66	1.13	1.89	1.50	0.93	0.38	6.90
55	E 9-C	0.07	0.43	0.57	0.71	0.84	1.82	1.62	0.96	0.38	7.40
56	H 1	0.29	0.19	0.51	1.21	2.21	2.33	1.27	0.96	0.42	9.39
57	H 2	0.15	0.18	0.41	0.95	2.00	2.28	1.32	0.97	0.42	8.68
58	H 3	0.06	0.10	0.10	0.53	1.61	2.14	1.42	1.01	0.42	7.39
59	H 4	0.00	0.08	0.07	0.35	1.33	1.94	1.52	1.02	0.42	6.73
60	H 5	0.00	0.10	0.10	0.37	1.16	1.82	1.55	1.03	0.42	6.55

APPENDIX 2 - TABLE III

TERRAIN CORRECTIONS FOR HAYFORD ZONES B TO J ON THE ATHABASKA GLACIER

Units of Milligals

No.	Station	B	C	D	E	F	G	H	I	J	Total
61	H 6	0.00	0.10	0.15	0.39	0.99	1.76	1.59	1.03	0.42	6.43
62	H 7	0.00	0.07	0.17	0.40	0.90	1.73	1.59	1.03	0.42	6.31
63	H 8	0.00	0.19	0.29	0.43	0.80	1.68	1.60	1.03	0.42	6.44
64	H 9	0.43	0.25	0.60	0.46	0.60	1.61	1.60	1.03	0.42	7.00
65	F 0	0.35	0.22	0.41	0.90	1.95	2.14	1.33	1.03	0.46	8.79
66	F 1	0.53	0.19	0.29	0.78	1.77	2.02	1.36	1.15	0.46	8.55
67	F 2	0.27	0.10	0.18	0.63	1.64	2.00	1.40	1.16	0.46	7.84
68	F 3	0.14	0.09	0.15	0.48	1.51	1.98	1.45	1.16	0.46	7.42
69	F 4	0.00	0.14	0.13	0.37	1.35	1.92	1.52	1.16	0.46	7.05
70	F 5	0.00	0.12	0.17	0.27	1.18	1.81	1.58	1.16	0.46	6.75
71	F 6	0.00	0.15	0.23	0.24	1.08	1.75	1.60	1.17	0.46	6.68
72	F 7	0.00	0.15	0.25	0.22	1.02	1.66	1.63	1.19	0.46	6.58
73	F 8	0.00	0.15	0.25	0.22	1.02	1.66	1.63	1.19	0.46	6.58
74	F 9	0.24	0.17	0.29	0.40	0.75	1.63	1.74	1.22	0.45	6.89
75	F 10	0.34	0.30	0.35	0.44	0.70	1.64	1.79	1.24	0.45	7.25
76	G 1	0.22	0.21	0.22	0.76	1.56	1.83	2.05	1.37	0.52	8.74
77	G 2	0.25	0.21	0.30	0.58	1.41	1.80	2.05	1.37	0.52	8.49
78	G 3	0.23	0.24	0.36	0.41	1.26	1.75	2.05	1.37	0.52	8.19
79	G 4	0.17	0.24	0.35	0.35	1.16	1.69	2.06	1.36	0.52	7.90
80	G 5	0.31	0.36	0.39	0.30	1.06	1.64	2.06	1.35	0.52	7.99
81	G 6	0.26	0.36	0.39	0.24	1.02	1.59	2.07	1.35	0.52	7.80
82	G 7	0.40	0.46	0.37	0.22	1.00	1.59	2.06	1.34	0.52	7.96
83	G 8	0.46	0.78	0.59	0.19	0.99	1.58	2.06	1.34	0.52	8.51
84	L 1	0.04	0.05	0.47	2.64	3.87	1.95	0.85	0.30	0.17	10.34
85	L 2	0.10	0.12	0.27	2.10	3.70	1.99	0.88	0.32	0.17	9.65
86	L 10	0.18	0.09	0.17	1.40	4.08	2.25	1.06	0.38	0.21	9.82
87	L 11	0.05	0.07	0.16	1.30	3.90	2.30	1.13	0.39	0.21	9.51
88	L 12	0.08	0.04	0.16	1.21	3.82	2.38	1.22	0.42	0.22	9.55
89	L 13	0.00	0.04	0.13	1.13	3.60	2.40	1.25	0.44	0.23	9.22
90	L 14	0.00	0.04	0.07	1.07	3.40	2.41	1.27	0.41	0.24	8.91

APPENDIX 2 - TABLE III

TERRAIN CORRECTIONS FOR HAYFORD ZONES B TO J ON THE ATHABASKA GLACIER

Units of Milligals

No.	Station	B	C	D	E	F	G	H	I	J	Total
91	L 15	0.00	0.06	0.06	1.01	3.19	2.42	1.32	0.48	0.25	8.79
92	L 16	0.00	0.11	0.03	1.02	3.17	2.43	1.41	0.53	0.26	8.96
93	L 18	0.00	0.04	0.01	0.95	2.70	2.43	1.49	0.60	0.28	8.50
94	L 19	0.00	0.03	0.01	0.86	2.27	2.42	1.46	0.63	0.29	7.97
95	L 20	0.00	0.02	0.01	0.86	0.88	2.35	1.42	0.66	0.31	7.51
96	L 22	0.00	0.02	0.01	0.73	1.46	2.23	1.37	0.72	0.33	6.87
97	L 23	0.00	0.03	0.04	0.63	1.40	2.21	1.32	0.76	0.35	6.74
98	L 24	0.00	0.05	0.05	0.65	1.40	2.20	1.30	0.78	0.36	6.79
99	L 25	0.00	0.06	0.13	0.62	1.40	2.11	1.30	0.83	0.37	6.82
100	L 26	0.10	0.08	0.10	0.68	1.40	2.09	1.30	0.87	0.37	6.99
101	L 27	0.16	0.14	0.08	0.68	1.39	2.00	1.38	0.88	0.38	7.09
102	L 28	0.14	0.11	0.13	0.60	1.30	1.97	1.39	0.95	0.39	6.98
103	L 29	0.14	0.12	0.12	0.50	1.15	1.90	1.44	0.99	0.40	6.76
104	L 31	0.14	0.04	0.13	0.28	1.00	1.71	1.60	1.10	0.44	6.44
105	L 33	0.19	0.15	0.25	0.24	1.00	1.68	1.68	1.23	0.47	6.89
106	L 34	0.16	0.18	0.34	0.26	1.00	1.60	1.75	1.26	0.48	7.03
107	L 35	0.18	0.21	0.40	0.30	0.99	1.58	1.81	1.27	0.49	7.23
108	L 36	0.18	0.23	0.44	0.26	1.00	1.58	1.98	1.33	0.51	7.51
109	Lake	0.00	0.09	0.22	0.84	1.66	1.93	2.54	1.68	0.77	9.73
110	Bridge	0.00	0.06	0.24	0.84	1.66	1.93	2.54	1.68	0.77	9.72
111	M 13	0.36	0.69	1.73	2.60	2.30	2.44	1.42	0.41	0.23	12.18
112	M 14	0.42	0.78	1.95	2.10	2.20	2.44	1.48	0.43	0.24	12.04
113	M 18	0.00	0.03	0.49	1.36	1.80	2.40	1.55	0.57	0.28	8.48
114	M 19	0.00	0.04	0.54	1.21	1.49	2.35	1.55	0.61	0.29	8.08
115	M 23	0.23	0.49	1.45	0.75	0.90	2.10	1.55	0.73	0.34	8.54
116	M 24	0.48	0.47	1.52	0.67	0.79	2.00	1.57	0.79	0.36	8.65
117	M 28	0.65	0.45	0.38	0.68	0.70	1.74	1.60	1.01	0.41	7.62
118	M 31	0.22	0.18	0.35	0.45	0.70	1.63	1.62	1.05	0.43	6.63
119	M 35	0.59	0.40	0.46	0.44	0.49	1.57	1.85	1.24	0.47	7.51
120	Gravel	1.31	0.34	1.48	4.26	3.84	2.10	0.92	0.45	0.20	14.90

APPENDIX 2 - TABLE III

TERRAIN CORRECTIONS FOR HAYFORD ZONES B TO J ON THE ATHABASKA GLACIER

Units of Milligals

No.	Station	B	C	D	E	F	G	H	I	J	Total
121	B	0.07	0.22	1.15	2.48	4.19	2.39	1.05	0.56	0.26	12.37
122	D	0.46	0.42	0.76	1.96	3.47	2.42	1.01	0.66	0.28	11.44
123	E	0.62	0.45	0.96	1.88	3.20	2.44	0.98	0.68	0.31	11.52
124	G	0.25	0.29	0.72	1.60	2.41	2.47	1.15	0.76	0.34	9.99
125	H	0.27	0.13	0.55	1.38	2.29	2.40	1.29	0.92	0.39	9.62

APPENDIX 3 - TABLE VI

RESULTS OF COMPUTER PROGRAM FOR THE ATHABASKA GLACIER

Gravity anomaly in units of milligals: Depth in feet.

Line 6666	Station	Model I	Model II	Model III	Maximum Depth I, II, III
A	1	4.90	3.94		700, 560 --
A	3	9.14	7.24		
A	5	12.03	10.40		
A	7	11.60	10.35		
B	1	10.82	9.82	9.93	1,070, 860, 1070
B	3	13.61	12.33	13.34	
L	12	15.13	13.51	15.34	
B	9	10.87	9.78	12.23	
B	10	5.11	4.54	7.19	
C	0	3.35	2.65		1020, 820
C	3	11.62	9.99		
C	5	14.35	12.54		
C	7	15.78	13.71		
C	9	15.86	13.73		
C	12	13.43	11.51		
C	14	9.72	8.29		
C	16	3.68	2.99		
D	1	8.97	7.47	8.20	1000, 800, 1000
D	2	11.32	9.28	10.51	
D	4	14.30	11.93	13.90	
D	6	15.43	13.20	15.37	
D	10	12.93	10.72	12.94	
D	11½	6.92	5.81	7.65	
E	0	5.88	5.04		800, 640
E	2	8.88	7.83		
E	3	11.82	10.14		
E	5	13.37	11.64		
E	7	12.46	10.70		
E	9C	7.23	6.16		

APPENDIX 2 - TABLE VI

RESULTS OF COMPUTER PROGRAM FOR THE ATHABASKA GLACIER

Gravity anomaly in units of milligals: Depth in feet.

Line 6666	Station	Model I	Model II	Model III	Maximum Depth I, II, III
H	1	6.08	5.38		700, 560
H	3	10.60	9.29		
H	5	11.56	10.03		
H	7	10.62	9.38		
H	9	6.27	5.54		
F	1	5.12	4.12		450, 370
F	3	7.52	6.68		
F	5	8.82	7.63		
F	7	8.69	7.46		
F	9	6.63	5.63		
F	10	4.13	3.22		
G	1	2.48	3.70	2.10	240, 490, 160
G	3	3.78	6.06	2.70	
G	6	4.08	5.73	2.70	
G	8	2.81	4.10	2.26	

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
1	1	115	21.1	49	29.8	2918	980,699.8	981,033.9	+175.1	-159.0	Road junction
2	2	115	20.9	49	27.2	2908	980,699.4	981,030.1	174.5	-156.2	
3	3	115	17.1	49	26.1	2873	980,697.4	981,028.5	172.4	-158.7	
4	4	115	13.5	49	22.3	2889	980,694.4	981,022.8	173.3	-155.1	Gallaway Shelter
5	5	115	10.5	49	19.3	2835	980,696.8	981,018.3	170.1	-151.4	Crossing - N Caithness
6	6	115	08.9	49	17.5	2880	980,693.7	981,015.7	172.8	-149.2	Tie (401)
7	7	115	09.9	49	17.2	2827	980,691.0	981,015.2	169.6	-154.6	
8	8	115	11.4	49	16.2	2711	980,692.2	981,013.8	162.7	-158.9	
9	9	115	11.5	49	14.9	2662	980,686.9	981,011.8	159.7	-165.2	
10	10	115	12.6	49	14.0	2620	980,688.4	981,010.5	157.2	-164.9	Tie (393)
11	11	115	11.3	49	12.7	2684	980,675.6	981,008.5	161.0	-171.9	BM 503 H 2
12	12	115	09.0	49	12.9	2876	980,665.4	981,008.8	172.6	-170.8	BM 503 H
13	13	115	06.4	49	10.8	2968	980,670.4	981,005.7	178.1	-157.2	BM 505 H
14	14	115	05.4	49	06.2	2734	980,679.8	980,998.7	164.0	-154.9	Grasmere
15	15	115	07.9	49	04.3	2680	980,675.8	980,996.0	160.8	-159.4	BM 507 H
16	16	115	13.3	49	07.5	2414	980,706.1	981,000.8	144.8	-149.9	
17	17	115	13.6	49	10.1	2404	980,709.7	981,004.6	144.2	-150.7	BM 503 H 7
18	18	115	13.6	49	11.6	2399	980,704.0	981,006.9	143.9	-159.0	Waldo (394)

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
19	19	115	15.1	49	14.6	2564	980,704.0	981,011.4	153.8	-153.6	
20	20	115	16.1	49	17.2	2470	980,712.7	981,015.2	148.2	-154.3	Mon. 82 S621
21	21	115	17.5	49	19.2	2632	980,708.4	981,018.2	157.9	-151.9	
22	22	115	17.8	49	21.1	2627	980,705.5	981,021.0	157.6	-157.9	Big Sand Br*
23	23	115	18.1	49	22.2	2703	980,694.5	981,022.7	162.2	-166.0	Jaffray (405
24	24	115	18.1	49	24.7	2792	980,689.6	981,026.4	167.5	-169.3	Tie Lake
25	25	115	20.1	49	23.6	2792	980,695.5	981,024.8	167.5	-161.8	
26	26	115	24.2	49	24.0	2560	980,718.9	981,025.4	153.6	-152.9	BM 133 D 2
27	27	115	22.3	49	24.1	2725	980,706.4	981,025.5	163.5	-155.6	
28	28	115	15.3	49	22.2	2810	980,689.2	981,022.7	168.6	-164.9	Rail crossing
29	29	115	22.0	49	28.9	2902	980,700.2	981,032.6	174.1	-158.3	
30	30	115	21.7	49	29.7	2996	980,695.7	981,033.8	179.8	-158.3	BM 135 D 4
31	1	115	27.2	49	28.2	2479	980,726.1	981,031.4	148.7	-156.6	BM 1350-2
32	2	115	24.1	49	29.9	2861	980,703.4	981,034.0	171.7	-158.9	BM 1350-3
33	3	115	27.1	49	29.3	2694	980,718.5	981,033.1	161.6	-153.0	Road Junctio
34	4	115	26.5	49	29.4	2780	980,714.3	981,033.2	166.8	-152.1	Roadside
35	5	115	26.0	49	29.5	2789	980,711.9	981,033.4	167.3	-154.2	Road Junction
36	6	115	25.3	49	29.6	2795	980,710.8	981,033.6	167.7	-155.1	Roadside

* Br. - Bridge

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
37	7	115	24.7	49	29.7	2820	980,708.8	981,033.7	169.2	-155.7	Roadside
38	8	115	21.7	49	29.7	2997	980,695.7	981,033.7	179.8	-158.2	BM 135 D-4 Tie 30
39	9	115	23.4	49	30.0	2911	980,699.4	981,034.1	174.7	-160.0	Stream
40	10	115	22.4	49	30.0	3003	980,697.3	981,034.1	180.2	-156.6	Roadside
41	11	115	21.2	49	29.8	2918	980,700.0	981,033.8	175.1	-158.7	Road Junction
42	12	115	21.3	49	29.4	2930	980,700.5	981,033.2	175.8	-156.9	Road Junction
43	13	115	21.9	49	28.9	2933	980,698.5	981,032.5	176.0	-158.0	Roadside
44	15	115	24.0	49	29.4	2838	980,709.3	981,033.2	170.3	-153.6	Road Junction
45	16	115	24.8	49	28.1	3012	980,693.2	981,031.3	180.7	-157.4	Roadside
46	17	115	25.9	49	28.3	2756	980,711.1	981,031.6	165.4	-155.1	Road Junction
47	18	115	37.3	49	24.1	4186*	980,635.5	981,025.3	251.2	-138.6	Road Junction
48	19	115	40.0	49	20.1	4531	980,612.3	981,019.4	271.9	-135.2	Bridge
49	20	115	39.2	49	20.8	4492	980,614.5	981,020.4	269.5	-136.4	Creek
50	21	115	38.4	49	22.0	4394	980,621.0	981,022.2	263.6	-137.6	Creek
51	22	115	37.9	49	22.7	4307	980,626.6	981,023.2	258.4	-138.2	Trail
52	23	115	37.6	49	23.6	4236	980,631.0	981,024.6	254.2	-139.4	Sawmill
53	24	115	36.3	49	24.7	4182	980,633.6	981,026.2	250.9	-141.7	Road Junction
54	25	115	35.6	49	25.4	4059	980,639.4	981,027.3	243.5	-144.4	Trail Junction

* Elevation for Nos. 47 to 55 inclusive are in doubt by ± 35 feet.

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
55	26	115	35.0	49	25.6	4266*	980,627.3	981,027.6	256.0	-144.3	Old sawmill
56	28	115	39.0	49	25.8	4150	980,634.6	981,027.9	249.0	-144.3	Trail
57	29	115	40.0	49	26.5	3836	980,654.5	981,028.9	230.2	-144.2	Road Junction
58	30	115	41.2	49	27.1	3597	980,667.3	981,029.9	215.8	-146.8	Bridge Joseph Cr.
59	31	115	42.1	49	27.7	3534	980,673.5	981,030.7	212.0	-145.2	Road Junction
60	32	115	42.5	49	28.0	3506	980,677.4	981,031.1	210.4	-143.3	Road Junction
61	33	115	42.9	49	28.3	3569	980,676.8	981,031.6	214.1	-140.7	Roadside
62	34	115	43.6	49	28.7	3505	980,680.6	981,032.2	210.3	-141.3	Road Junction
63	35	115	44.3	49	29.3	3367	980,690.6	981,033.1	202.0	-140.5	Roadside
64	36	115	45.0	49	30.0	3118	980,706.2	981,034.1	187.1	-140.8	Culvert
65	37	115	29.2	49	32.7	2773	980,713.5	981,038.1	166.4	-158.2	Road
66	38	115	36.1	49	36.7	2753	980,716.8	981,044.0	165.2	-162.0	Road Junction
67	39	115	30.0	49	33.6	2807	980,711.8	981,039.5	168.4	-159.3	Road Junction
68	40	115	31.5	49	34.0	2835	980,707.6	981,040.1	170.1	-162.4	Roadside
69	41	115	33.2	49	34.3	2837	980,706.3	981,040.5	170.2	-164.0	Road Junction
70	43	115	35.6	49	36.1	2620	980,723.5	981,043.2	157.2	-162.5	Bridge
71	45	115	31.0	49	34.9	2871	980,704.5	981,041.4	172.3	-164.6	Trail Junction
72	46	115	31.5	49	35.2	2881	980,704.5	981,041.8	172.9	-164.4	Trail

* Elevation for Nos. 47 to 55 inclusive are in doubt by ± 35 feet.

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
73	47	115	32.2	49	35.7	2914	980,705.0	981,042.6	174.8	-162.8	Trail Junction
74	48	115	33.1	49	36.4	2957	980,704.8	981,043.6	177.4	-161.4	Road bend
75	49	115	34.5	49	37.1	2924	980,708.4	981,044.9	175.4	-161.1	Road Junction
76	50	115	33.8	49	33.1	2776	980,707.8	981,039.5	166.6	-165.1	Road Junction
77	51	115	33.5	49	33.3	2833	980,705.9	981,038.6	170.0	-162.7	Road
78	52	115	32.7	49	32.4	2794	980,711.1	981,037.7	167.6	-159.0	Road
79	53	115	32.7	49	31.6	2485	980,733.4	981,036.5	149.1	-154.0	Fenwick
80	54	115	23.5	49	28.8	2723	980,715.9	981,032.3	163.4	-153.0	Trail at Fence
81	55	115	26.0	49	30.3	2842	980,703.8	981,034.5	170.5	-160.2	House
82	56	115	26.0	49	29.9	2799	980,710.0	981,034.0	167.9	-156.1	Gate
83	57	115	25.6	49	29.5	2807	980,711.2	981,033.4	168.4	-153.8	Road
84	58	115	25.8	49	29.0	2777	980,712.3	981,032.6	166.6	-153.7	Road
85	59	115	19.7	49	31.9	2989	980,685.2	981,037.0	179.3	-172.5	Bridge
86	60	115	19.7	49	34.1	3103	980,694.0	981,040.2	186.2	-160.0	Bridge
87	61	115	19.3	49	35.3	3177	980,696.8	981,042.0	190.6	-154.6	Bridge
88	62	115	19.6	49	35.0	3294	980,690.4	981,041.5	197.6	-153.5	Gully
89	63	115	19.8	49	34.6	3171	980,691.8	981,041.0	190.3	-158.9	Bridge
90	64	115	19.3	49	33.8	3169	980,688.1	981,039.8	190.1	-161.6	Road

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
91	65	115	18.8	49	33.4	3098	980,692.4	981,039.2	185.9	-160.9	Gully
92	66	115	18.9	49	32.7	3061	980,690.7	981,038.1	183.7	-163.7	Road
93	67	115	13.6	49	39.0	3358	980,692.8	981,047.4	201.5	-153.1	
94	68	115	15.3	49	37.9	3365	980,694.4	981,045.8	201.9	-149.5	Bridge
95	69	115	16.4	49	37.1	3405	980,691.7	981,044.6	204.3	-148.6	Old Cabin
96	70	115	18.3	49	36.5	3534	980,697.8	981,043.8	212.0	-152.0	Bridge
97	71	115	31.3	49	28.4	2697	980,719.2	981,031.7	161.8	-150.7	Railroad
98	72	115	28.1	49	28.0	2588	980,721.5	981,031.1	155.3	-154.3	Railroad
99	73	115	29.8	49	27.9	2777	980,712.7	981,031.0	166.6	-151.7	Trail Junction
100	74	115	33.4	49	26.5	3615	980,668.8	981,028.9	216.9	-143.2	Trail Junction
101	75	115	33.0	49	26.4	3494	980,673.8	981,028.8	209.6	-145.4	Trail
102	76	115	32.5	49	26.4	3288	980,685.4	981,028.8	197.3	-146.1	Trail
103	77	115	31.9	49	26.2	3161	980,688.3	981,028.4	189.7	-150.4	Road Junction
104	78	115	30.2	49	26.4	2757	980,712.8	981,028.8	165.4	-150.6	Lake
105	79	115	38.0	49	36.0	2702	980,725.1	981,037.1	162.1	-149.9	Railway
106	80	115	36.1	49	31.1	2701	980,724.5	981,035.7	162.1	-149.1	Railway
107	81	115	35.2	49	20.2	2702	980,724.9	981,034.4	162.1	-147.4	Railway
108	82	115	34.2	49	29.4	2716	980,721.2	981,033.2	163.0	-149.0	Railway

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
109	83	115	32.8	49	29.7	2782	980,719.2	981,033.6	166.9	-147.5	Road
110	84	115	33.3	49	29.3	2728	980,721.2	981,033.1	163.7	-148.2	Road Junction
112	85	115	32.9	49	29.8	2750	980,718.4	981,032.9	165.0	-149.5	Quarry
113	86	115	32.8	49	28.3	2888	980,708.4	981,031.6	173.3	-149.9	Quarry
114	87	115	32.8	49	28.7	2709	980,720.2	981,032.2	162.5	-149.5	Railway
115	88	115	32.5	49	28.9	2742	980,719.0	981,032.5	164.5	-149.0	Highway
116	89	115	51.7	49	23.7	3140	980,697.0	981,024.7	188.4	-139.3	BM 178.C
117	90	115	49.4	49	21.0	3169	980,688.3	981,020.7	190.1	-142.3	Highway
118	91	115	49.4	49	21.7	3196	980,690.1	981,021.7	191.8	-139.8	Highway
119	92	115	49.4	49	22.1	3123	980,694.4	981,022.3	187.4	-140.5	Highway
120	93	115	49.5	49	22.4	3055	980,698.7	981,022.8	183.3	-140.8	Bridge
121	94	115	49.9	49	22.7	3054	980,695.6	981,023.2	183.2	-144.4	Highway
122	95	115	50.3	49	22.8	3072	980,697.8	981,023.4	184.3	-141.3	Road Junction
123	96	115	51.0	49	22.9	3098	980,699.8	981,023.5	185.9	-137.8	Railroad
124	97	115	51.2	49	23.3	3106	980,699.4	981,024.1	186.4	-138.3	Culvert
125	98	115	20.4	49	31.5	3011	980,683.5	981,036.3	180.7	-172.1	Road
126	99	115	20.7	49	30.8	3050	980,685.7	981,035.3	183.0	-166.6	Stream
127	100	115	20.8	49	30.5	2976	980,689.9	981,034.8	178.6	-166.3	Road

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
128	31 S	115	18.3	49	26.5	2921	980,695.8	981,028.9	175.3	-157.8	Road Junction
129	32 S	115	18.4	49	25.1	2800	980,693.7	981,026.8	168.0	-165.1	Road
130	33 S	115	17.6	49	24.0	2757	980,690.9	981,025.2	165.4	-168.9	Road Bend
131	34 S	115	20.2	49	24.3	2812	980,694.3	981,025.6	168.7	-162.6	Trail
132	35 S	115	20.8	49	26.0	3114	980,685.3	981,028.2	186.8	-156.1	Trail
133	36 S	115	20.9	49	25.1	2795	980,699.6	981,026.8	167.7	-159.5	Trail Junction
134	37 S	115	23.3	49	25.6	2822	980,703.2	981,027.6	169.3	-155.1	Trail Junction
135	38 S	115	25.8	49	27.4	2524	980,721.9	981,030.2	151.4	-156.9	Road Junction
136	39 S	115	24.5	49	27.1	3100	980,689.2	981,029.8	186.0	-154.6	Trail
137	40 S	115	23.5	49	26.6	3036	980,690.5	981,029.0	182.2	-156.3	Old Cabin
138	41 S	115	24.5	49	25.5	2560	980,720.1	981,027.4	153.6	-153.7	Road Junction
139	42 S	115	15.4	49	23.7	2835	980,688.0	981,024.7	170.1	-166.6	Road Junction
140	43 S	115	16.5	49	22.8	2762	980,689.4	981,023.4	165.7	-168.3	Road Junction
141	44 S	115	14.3	49	22.3	2857	980,689.4	981,022.6	171.4	-161.8	Bridge
142	45 S	115	13.9	49	23.9	2963	980,691.8	981,025.0	177.8	-155.4	Road
143	46 S	115	12.3	49	24.1	3193	980,673.1	981,025.3	191.6	-160.6	Trail
144	47 S	115	8.8	49	25.1	3553	980,652.0	981,026.8	213.2	-161.6	Trail Junction
145	48 S	115	9.7	49	24.0	3436	980,656.6	981,025.2	206.2	-162.4	Road Junction

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
146	49 S	115	11.1	49	23.4	3403	980,663.2	981,024.3	204.2	-156.9	Road turn
147	50 S	115	12.2	49	20.4	2772	980,698.4	981,019.8	166.3	-155.1	Trail
148	51 S	115	12.1	49	21.2	2849	980,697.3	981,021.0	170.9	-152.8	Road Junction
149	52 S	115	12.3	49	18.5	2755	980,695.7	981,017.0	165.3	-156.0	Trail
150	53 S	115	10.9	49	18.2	2793	980,696.1	981,016.5	167.6	-152.8	Road Junction
151	54 S	115	12.9	49	16.6	2644	980,698.3	981,014.1	158.6	-157.2	Bridge
152	55 S	115	14.0	49	17.6	2638	980,701.5	981,015.6	158.3	-155.8	Trail Junction
153	56 S	115	14.6	49	19.2	2682	980,702.4	981,018.0	160.9	-154.7	Suzanne Lake
154	57 S	115	13.4	49	15.4	2643	980,694.4	981,012.3	158.6	-159.3	Road Junction
155	(14)	115	45.6	49	31.1	3011	980,715.8	981,035.7	180.6	-139.3	Cranbrook P.O.
156	1	115	40.7	49	34.65	2810	980,723.7	981,041.0	168.6	-148.7	Cross Road Hwy3
157	2	115	39.95	49	34.10	2789	980,723.4	981,040.2	167.4	-149.4	Hwy. white post
158	3	115	39.1	49	33.45	2711	980,726.1	981,039.2	162.7	-150.4	Monument 7/338
159	4	115	38.75	49	33.00	2699	980,725.0	981,038.6	162.0	-151.6	" 11/338
160	5	115	38.2	49	32.50	2694	980,724.9	981,037.8	161.6	-151.3	" 14/338
161	(407)	115	36.95	49	31.55	2691	980,724.2	981,036.4	161.5	-150.7	Rampart station
162	7	115	36.15	49	31.14	2701	980,722.2	981,035.8	162.0	-151.6	BM 168 D
163	8	115	36.10	49	31.10	2701	980,722.3	981,035.7	162.0	-151.4	Rail crossing 23/338

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
164	9	115	35.4	49	30.72	2729	980,720.8	981,035.1	163.7	-150.6	Monument 28/338
165	10	115	35.2	49	30.58	2707	980,722.9	981,035.0	162.4	-149.7	Road Junction
166	(13)	115	25.5	49	25.40	2489	980,724.4	981,027.2	149.3	-153.5	Wardner Station
167	12	115	26.2	49	24.66	2725	980,712.4	981,026.1	163.5	-150.2	
168	13	115	26.25	49	24.19	2791	980,708.6	981,025.5	167.5	-149.4	
169	14	115	26.5	49	23.00	2931	980,701.4	981,023.7	175.9	-146.4	
170	15	115	26.75	49	25.80	2602	980,719.0	981,027.8	156.1	-152.7	Lund Lake
171	16	115	27.9	49	25.62	2774	980,710.8	981,027.6	166.4	-150.4	
172	17	115	29.3	49	25.90	2748	980,712.8	981,028.0	164.9	-150.3	Ha Ha Lake
173	18	115	26.2	49	25.83	2523	980,721.5	981,027.9	151.4	-155.0	Golf Course
174	19	115	25.9	49	26.13	2523	980,721.4	981,028.4	151.4	-155.6	Hwy. - opposite M78
175	20	115	28.1	49	28.01	2573	980,719.7	981,031.1	154.4	-157.0	Hwy. opposite Tokay
176	21	115	37.0	49	32.55	2656	980,725.1	981,037.9	159.4	-153.4	Power Line
177	22	115	37.65	49	32.07	2679	980,725.3	981,037.2	160.7	-151.2	Monument 13/338
178	23	115	24.35	49	24.35	2461	980,725.6	981,025.7	147.7	-152.4	

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
179	24	115	24.2	49	24.02	2562	980,719.2	981,025.2	153.7	-152.3	BM 133 D-2
180	25	115	24.1	49	23.89	2618	980,715.4	981,025.0	157.1	-152.5	
181	26	115	23.85	49	23.45	2608	980,716.0	981,024.4	156.5	-151.9	
182	27	115	23.1	49	22.5	2622	980,715.6	981,022.9	157.3	-150.0	Rail line
183	28	115	21.95	49	21.62	2660	980,712.7	981,021.6	159.6	-149.3	Colvalli
184	(405)	115	18.1	49	22.20	2703	980,694.5	981,022.5	162.2	-165.8	Jaffrey station
185	30	115	18.25	49	23.05	2743	980,692.4	981,023.7	164.6	-166.7	
186	31	115	18.3	49	23.22	2738	980,692.0	981,024.0	164.3	-167.7	Road Junction
187	32	115	18.1	49	23.60	2746	980,690.3	981,024.6	164.8	-169.5	
188	(12)	115	06.55	49	18.07	3088	980,677.4	981,016.4	185.3	-153.7	Elko Station
189	34	115	07.6	49	17.03	2957	980,688.6	981,014.8	177.4	-148.8	Hwy. 93 south
190	35	115	07.6	49	16.36	2928	980,689.9	981,013.8	175.7	-148.2	
191	36	115	07.9	49	15.28	2894	980,686.7	981,012.2	173.6	-151.9	
192	37	115	08.6	49	13.70	2813	980,676.0	981,009.8	168.8	-165.0	
193	38	115	09.1	49	12.70	2756	980,669.1	981,008.3	165.4	-173.8	Road Junction (waldo)
194	39	115	08.5	49	11.92	2501	980,684.0	981,007.2	150.0	-173.2	Elk River Br.
195	40	115	07.9	49	11.58	2815	980,666.5	981,006.7	168.9	-171.3	
196	41	115	07.7	49	09.75	2857	980,668.1	981,003.9	171.4	-164.4	

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

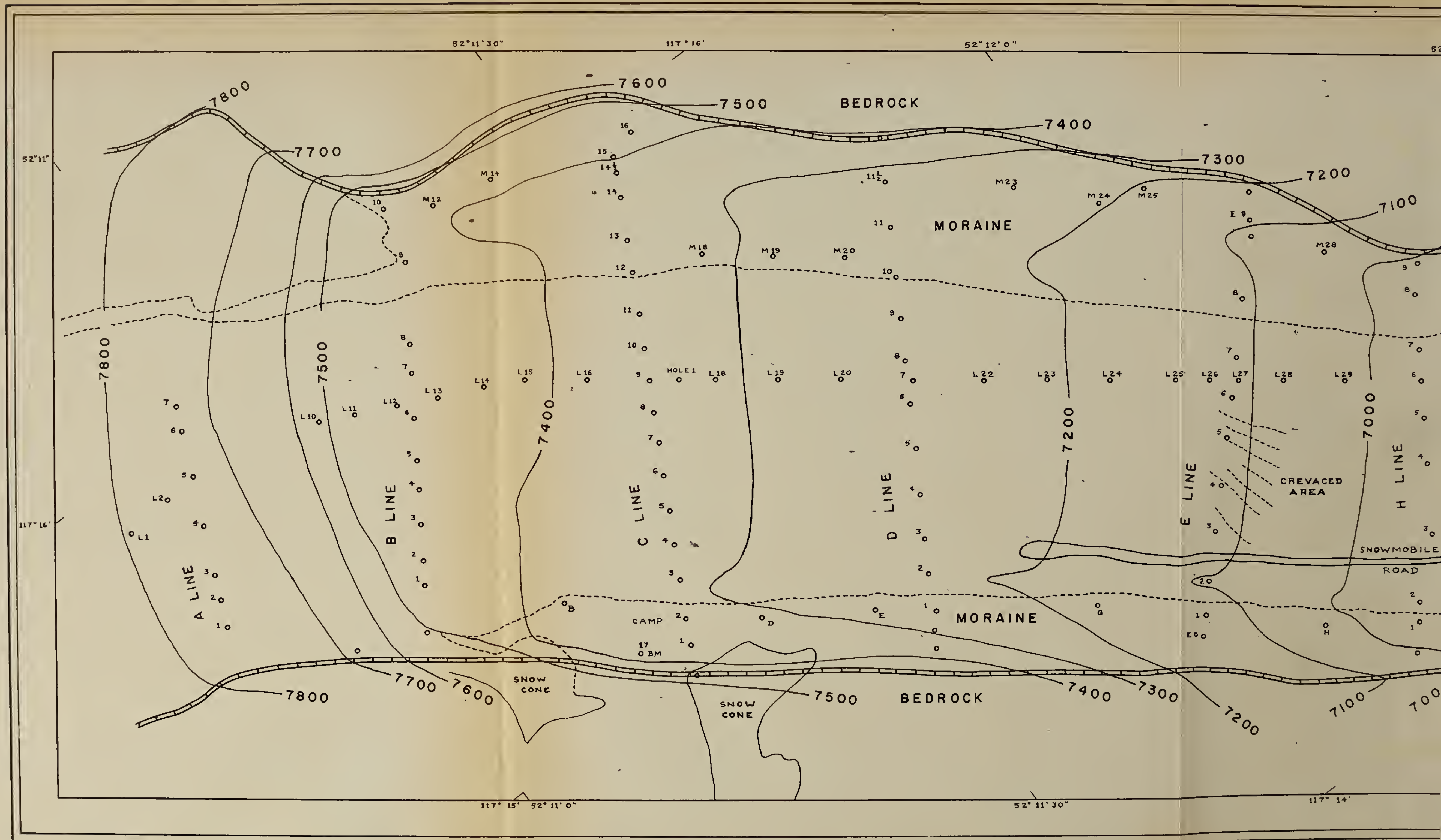
No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
197	42	115	05.9	49	08.70	2798	980,679.6	981,002.4	167.9	-154.9	Monument 57/144
198	43	115	05.6	49	07.38	2768	980,680.6	981,000.4	166.1	-153.7	School 54/15
199	44	115	05.4	49	06.20	2735	980,680.7	981,998.7	164.1	-153.9	Grasmere Gas Pump
200	45	115	05.5	49	06.95	2797	980,680.0	980,999.8	167.8	-152.0	Monument 6/8
201	46	115	04.4	49	18.6	3129	980,668.7	981,017.1	187.7	-160.7	
202	47	115	01.2	49	19.7	3130	980,662.0	981,018.8	187.8	-169.0	
203	48	115	00.6	49	22.1	3134	980,669.5	981,022.3	188.0	-164.8	
204	(403)	115	00.8	49	23.3	3139	980,670.7	981,024.1	188.3	-165.1	Morrissey Station
205	50	115	03.2	49	26.0	3179	980,669.2	981,028.1	190.7	-168.2	
206	51	115	04.6	49	28.6	3236	980,674.6	981,032.0	194.2	-163.2	Lizard Creek
207	(9)	115	03.3	49	30.2	3313	980,672.6	981,034.4	198.8	-163.0	Fernie
208	52	115	43.6	49	28.66	3505	980,680.6	981,032.1	210.3	-141.2	Road Junction Tie (62)
209	53	115	42.4	49	27.94	3516	980,676.6	981,031.0	211.0	-143.4	Road
210	54	115	41.9	49	27.35	3567	980,671.3	981,030.2	214.0	-144.9	
211	55	115	41.2	49	27.15	3597	980,667.2	981,029.9	215.8	-146.9	Joseph Creek Tie (58)
212	56	115	40.5	49	26.80	3791	980,656.0	981,029.3	227.5	-145.8	
213	57	115	39.2	49	26.25	4089	980,635.1	981,028.5	245.3	-148.1	
214	58	115	43.7	49	27.86	3664	980,669.6	981,030.9	219.8	-141.5	Road Junction

APPENDIX Ia - TABLE IIa

PRINCIPAL FACTS FOR GRAVITY STATIONS

Cranbrook - Elko Area

No.	Field No.	Longitude		Latitude		Elevation	Observed Gravity	Theoretical Gravity ( )	Bouguer and Free Air Correction	Bouguer Anomaly	Comments
		°	'	°	'	feet	milligals	milligals	milligals	milligals	
215	59	115	43.6	49	27.48	3875	980,655.0	981,030.3	232.5	-142.8	
216	60	115	43.5	49	26.82	3944	980,648.5	981,029.4	236.6	-144.3	
217	61	115	43.5	49	26.57	3995	980,644.6	981,029.0	239.7	-144.7	
218	62	115	43.2	49	26.28	4149	980,635.4	981,028.6	248.9	-144.3	
219	63	115	43.0	49	26.08	4219	980,629.7	981,028.3	253.1	-145.5	
220	64	115	42.7	49	25.80	4295	980,624.7	981,027.8	257.7	-145.4	
221	65	115	06.2	49	17.00	3061	980,681.5	981,014.7	183.7	-149.5	
222	66	115	06.0	49	16.50	3062	980,681.2	981,014.0	183.7	-149.1	
223	67	115	06.1	49	16.20	3060	980,680.9	981,013.6	183.6	-149.1	
224	68	115	06.9	49	16.08	2922	980,689.9	981,013.4	175.3	-148.2	
225	69	115	07.9	49	15.50	2912	980,689.7	981,012.5	174.7	-148.1	
226	70	115	07.3	49	14.83	3317	980,661.6	981,011.5	199.0	-150.9	Sheep Mountain
227	71	115	06.5	49	15.54	3563	980,647.5	981,012.6	213.8	-151.3	Sheep Mountain
228	72	115	08.1	49	14.02	2879	980,685.7	981,010.3	172.7	-151.9	Highway 98/144
229	73	115	08.6	49	13.45	2857	980,671.2	981,009.5	171.4	-166.9	
230	74	115	08.4	49	12.61	2904	980,665.8	981,008.2	174.2	-168.2	
231	75	115	07.6	49	12.64	2930	980,667.1	981,008.3	175.8	-165.4	
232	76	115	08.1	49	12.60	2942	980,673.1	981,008.2	176.5	-158.6	near Riverbank
233	77	115	08.3	49	13.80	2943	980,671.8	981,010.0	176.6	-161.6	Sheep Mountain
234	78	115	08.4	49	13.80	2835	980,677.0	981,010.0	170.1	-162.9	Road Junction



52°11'30"
117°16'
52°12'0"
52°11'
117°16'
7800
7700
7600
7500
7400
7300
7200
7100
7000
BEDROCK
MORAINE
A LINE
B LINE
C LINE
D LINE
E LINE
H LINE
CREVACED AREA
SNOWMOBILE
ROAD
CAMP
17 O BM
SNOW CONE
HOLE 1
117° 15'
52° 11' 0"
52° 11' 30"
117° 14'

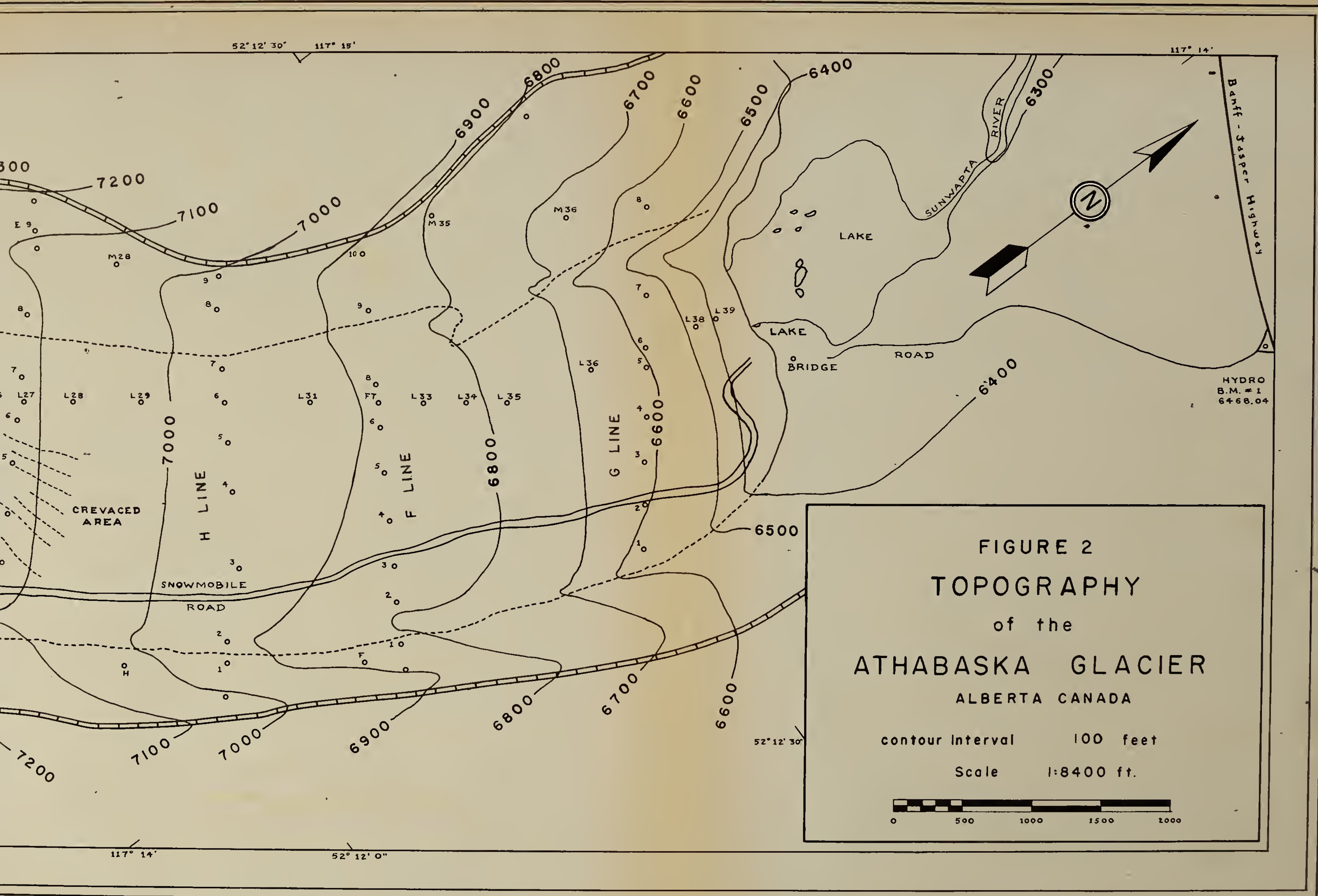


FIGURE 2

TOPOGRAPHY

of the

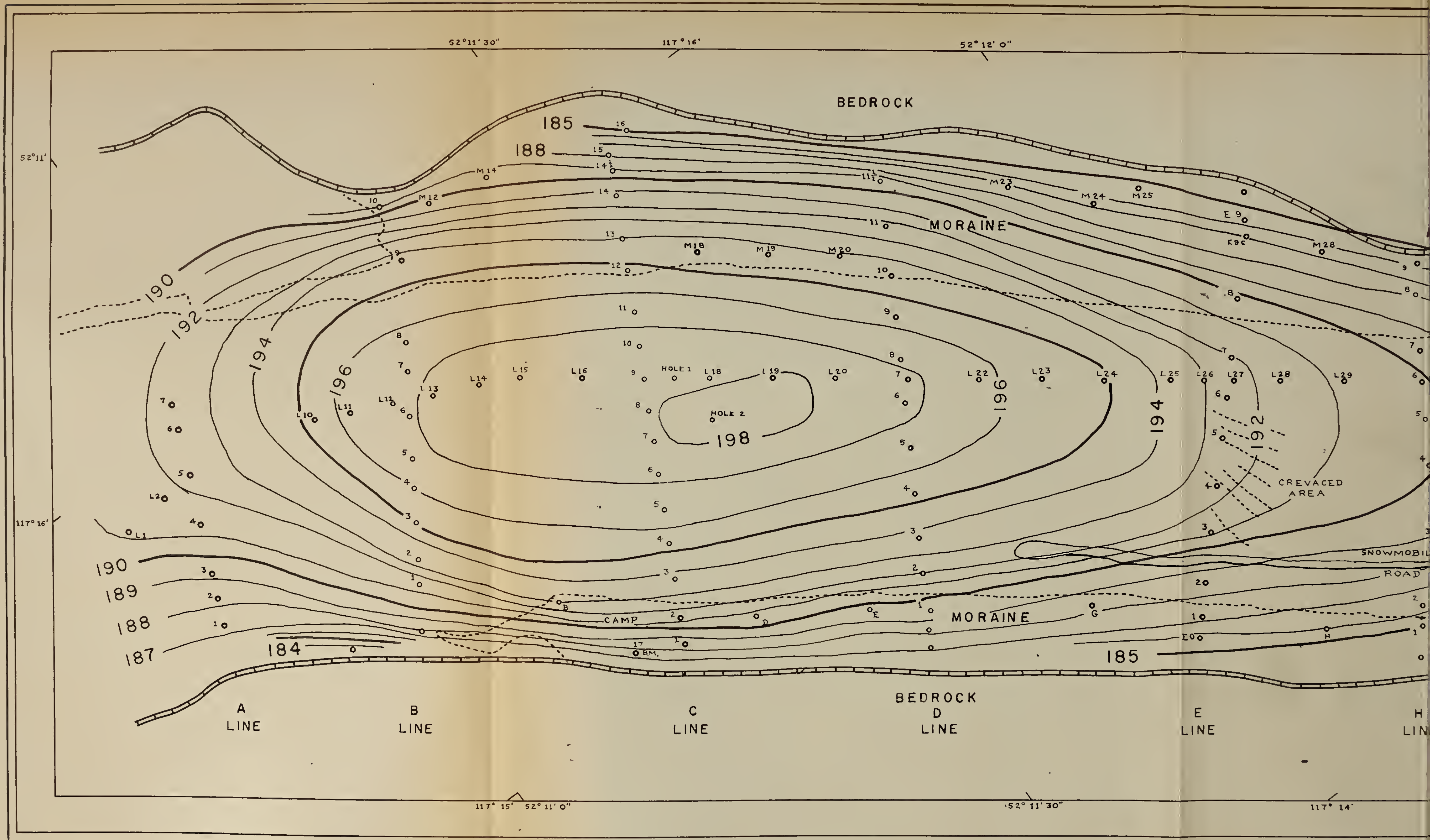
ATHABASKA GLACIER

ALBERTA CANADA

contour interval 100 feet

Scale 1:8400 ft.

0 500 1000 1500 2000



52°11'30"
117°16'
52°12'0"
BEDROCK
MORAINE
CREVACED AREA
SNOWMOBILE ROAD
CAMP
MORAINE
BEDROCK
HOLE 1
HOLE 2
185
188
190
192
194
196
198
189
187
184
A LINE
B LINE
C LINE
D LINE
E LINE
H LINE
52°11'
117°16'
117°15' 52°11'0"
52°11'30"
117°14'

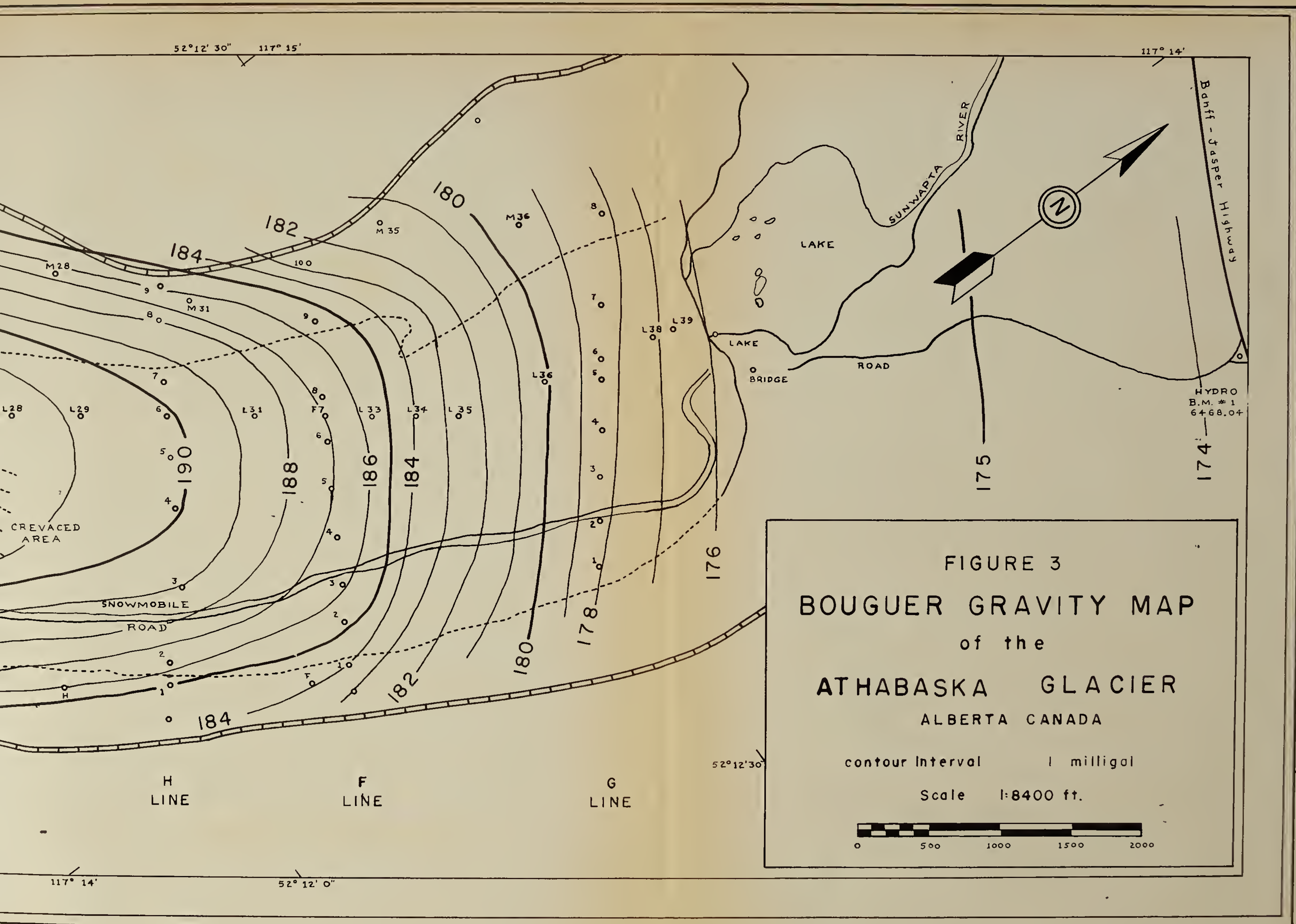


FIGURE 3

BOUGUER GRAVITY MAP

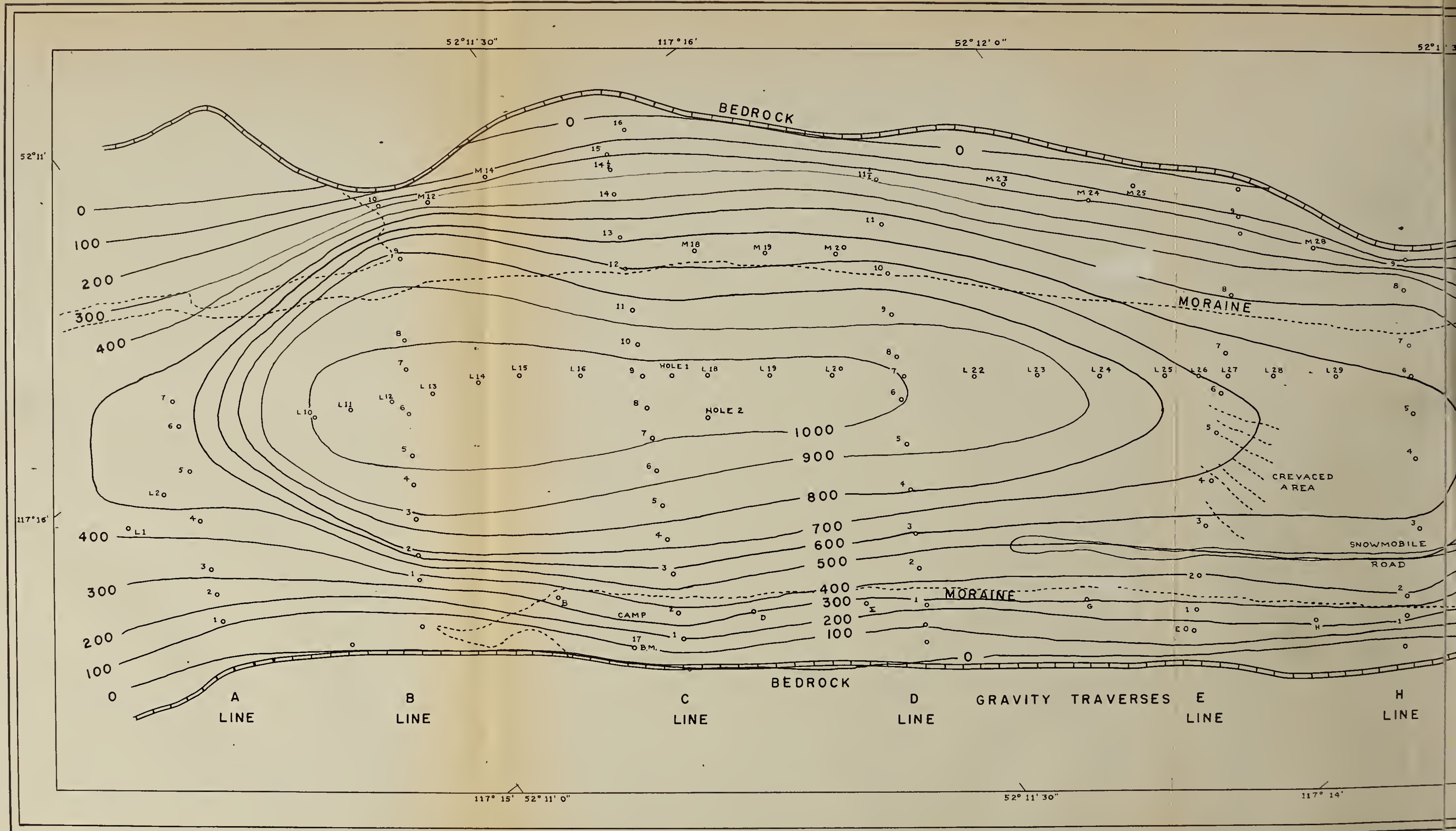
of the

ATHABASKA GLACIER

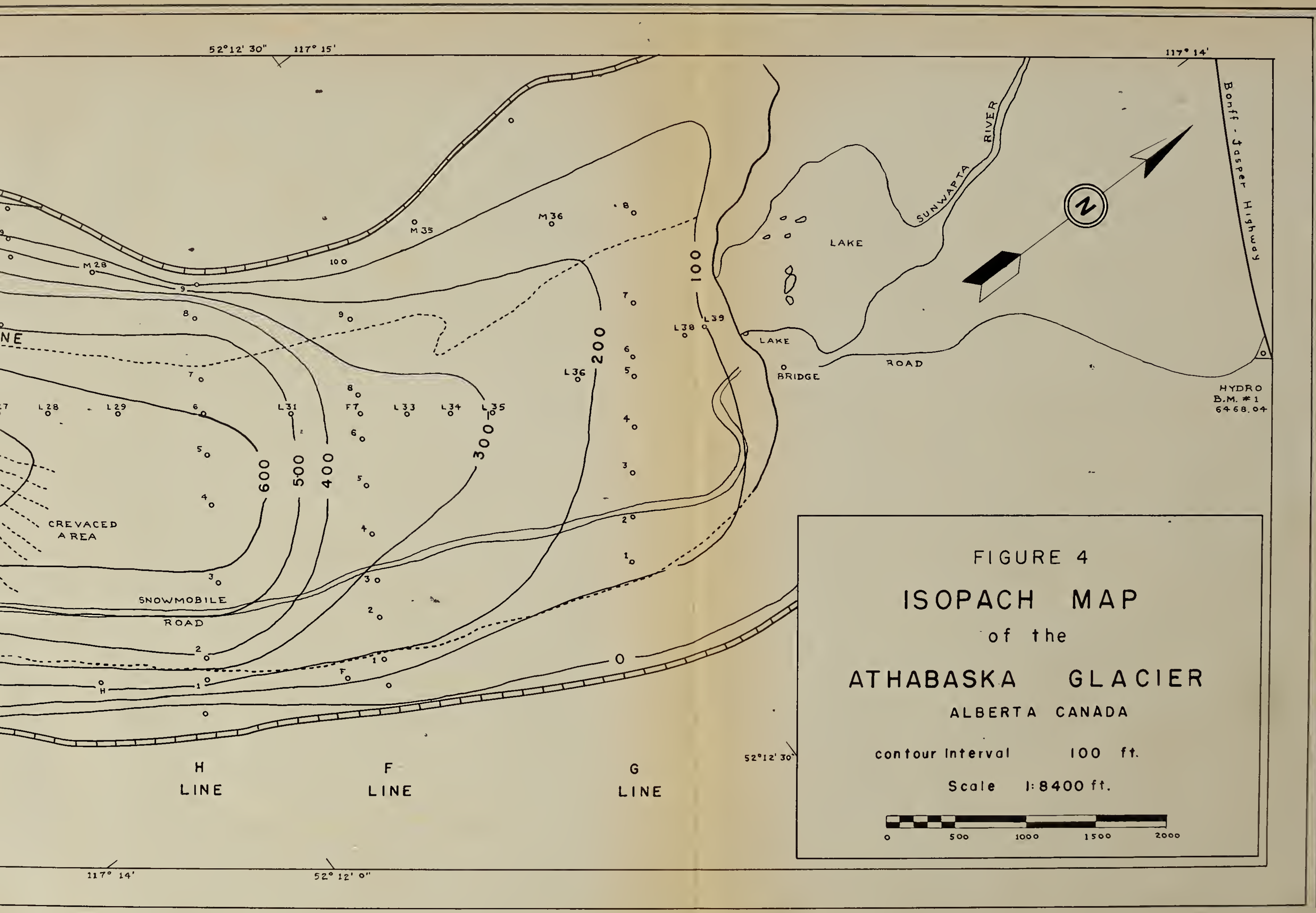
ALBERTA CANADA

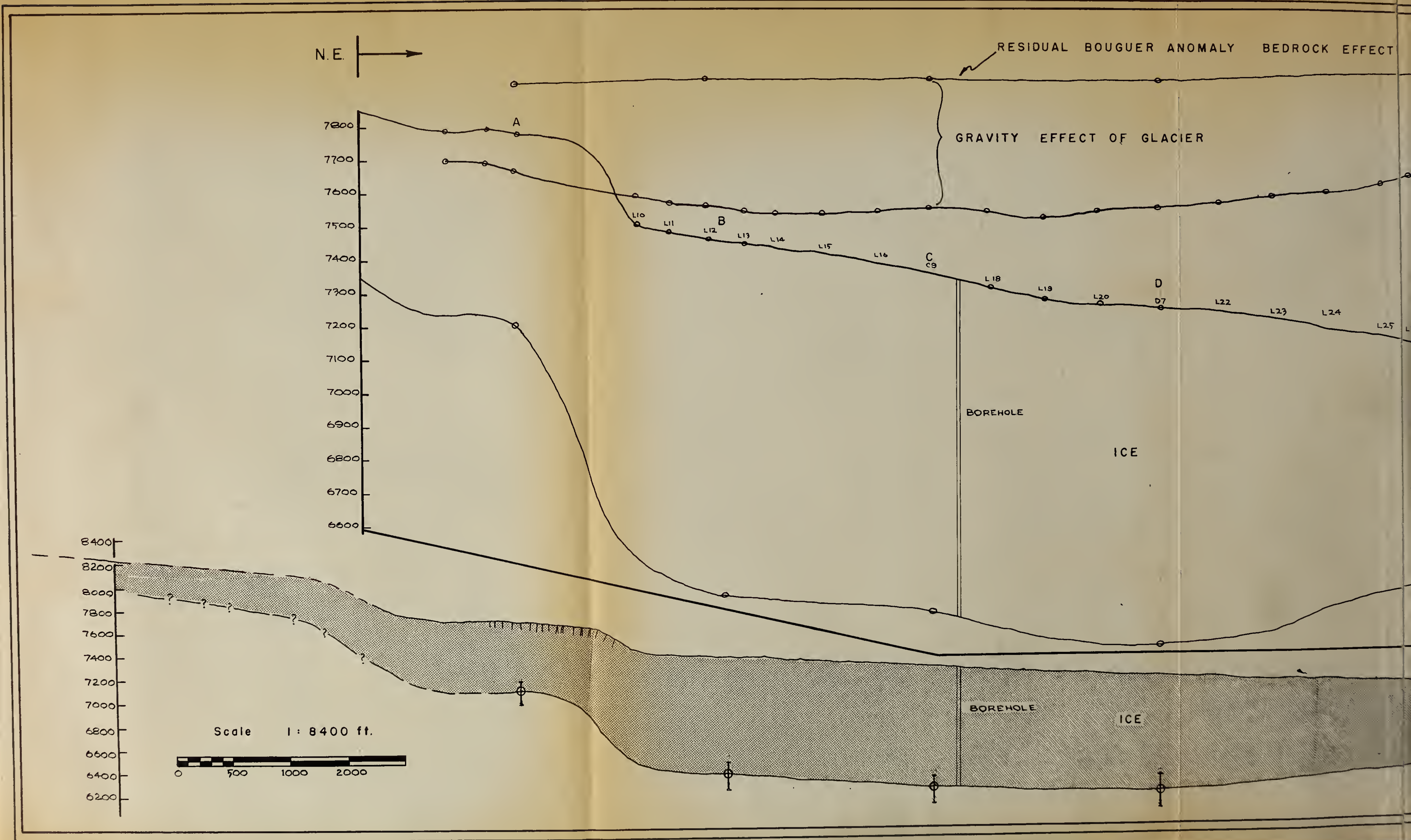
contour interval 1 milligal

Scale 1:8400 ft.



52°11'30"
117°16'
52°12'0"
52°11'
117°16'
BEDROCK
MORAINE
CREVACED AREA
SNOWMOBILE ROAD
HOLE 1
HOLE 2
CAMP
B.M.
0
100
200
300
400
500
600
700
800
900
1000
BEDROCK
A LINE
B LINE
C LINE
D LINE
GRAVITY TRAVERSES
E LINE
H LINE
117° 15'
52° 11' 0"
52° 11' 30"
117° 14'


52°12' 30"
117° 15'
117° 14'
Banff - Jasper Highway
SUNWAPTA RIVER
LAKE
LAKE
BRIDGE
ROAD
HYDRO
B.M. # 1
6468.04
M 35
M 36
M 28
100
200
300
400
500
600
0
L 28
L 29
L 31
F 7
L 33
L 34
L 35
L 36
L 38
L 39
CREVACED
AREA
SNOWMOBILE
ROAD
H
LINE
F
LINE
G
LINE
52°12' 30"
117° 14'
52° 12' 0"
FIGURE 4
ISOPACH MAP
of the
ATHABASKA GLACIER
ALBERTA CANADA
contour Interval 100 ft.
Scale 1:8400 ft.
0
500
1000
1500
2000



N.E.
RESIDUAL BOUGUER ANOMALY BEDROCK EFFECT
GRAVITY EFFECT OF GLACIER
A
B
C
D
L10
L11
L12
L13
L14
L15
L16
C9
L18
L19
L20
D7
L22
L23
L24
L25
7800
7700
7600
7500
7400
7300
7200
7100
7000
6900
6800
6700
6600
BOREHOLE
ICE
8400
8200
8000
7800
7600
7400
7200
7000
6800
6600
6400
6200
BOREHOLE
ICE
Scale 1 : 8400 ft.
0
500
1000
2000

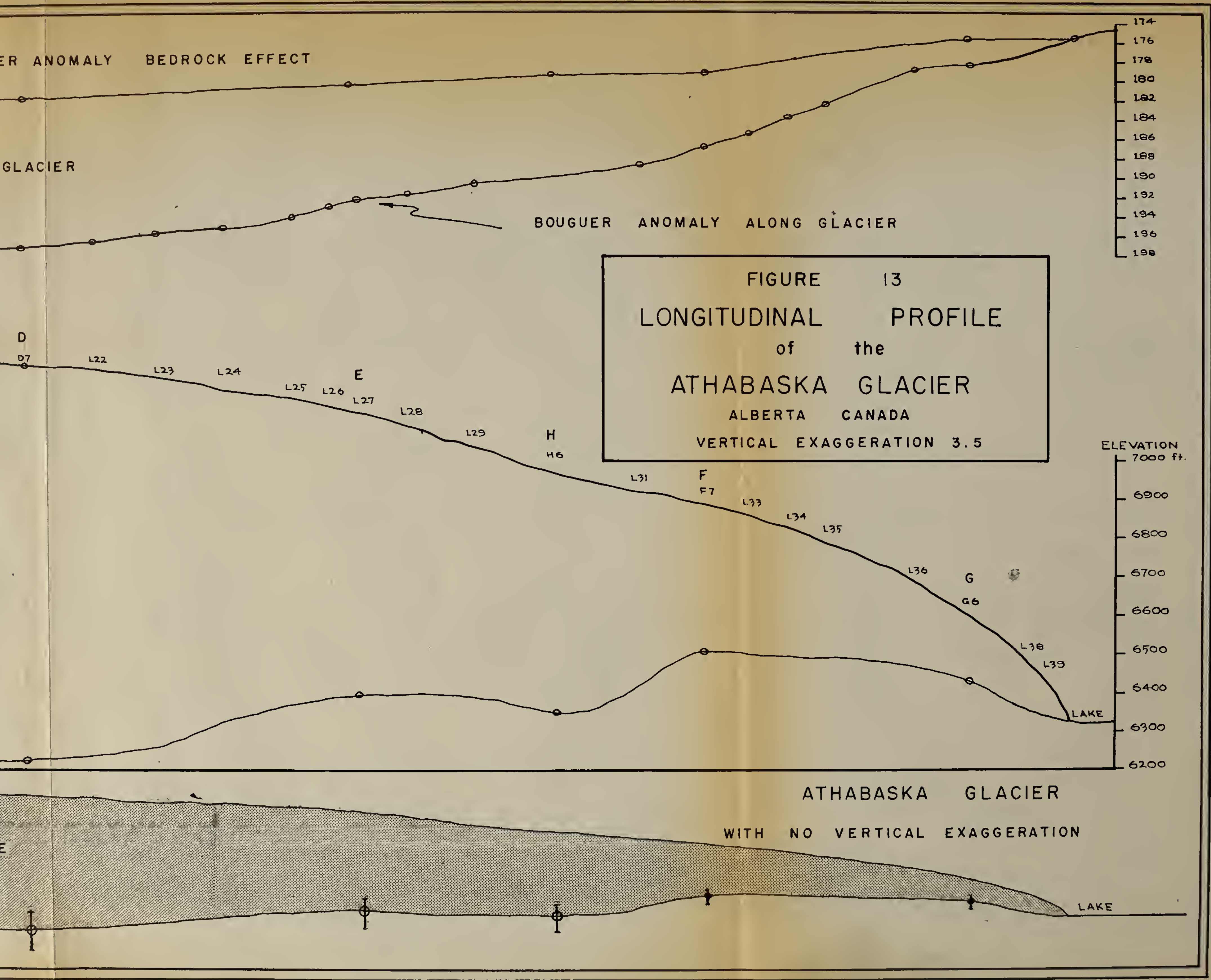


FIGURE 13
LONGITUDINAL PROFILE
of the
ATHABASKA GLACIER
ALBERTA CANADA
VERTICAL EXAGGERATION 3.5

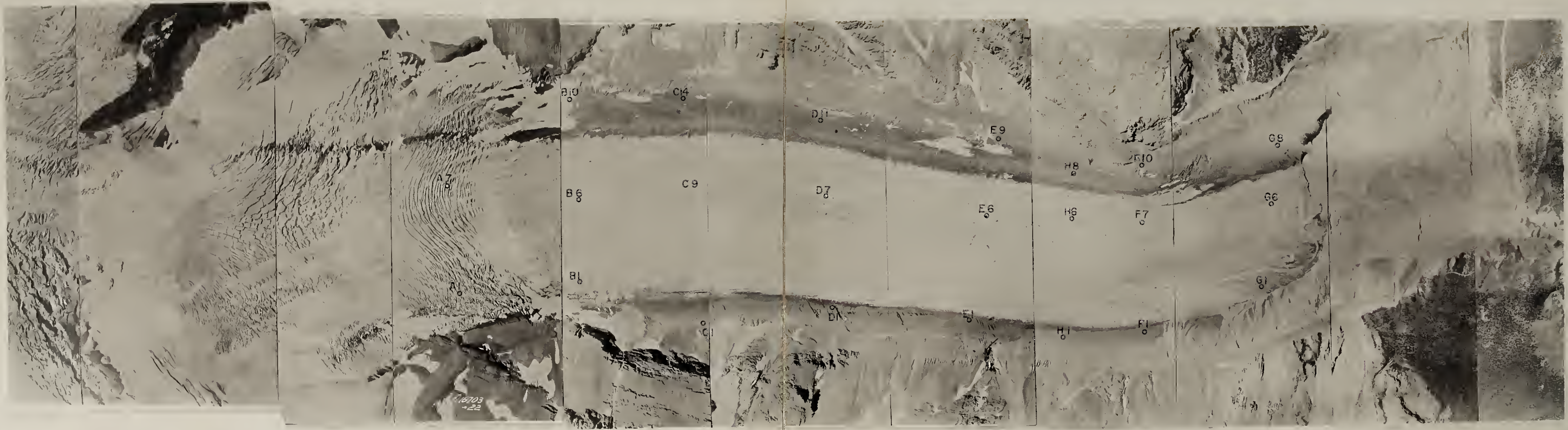


PLATE II. ATHABASKA GLACIER

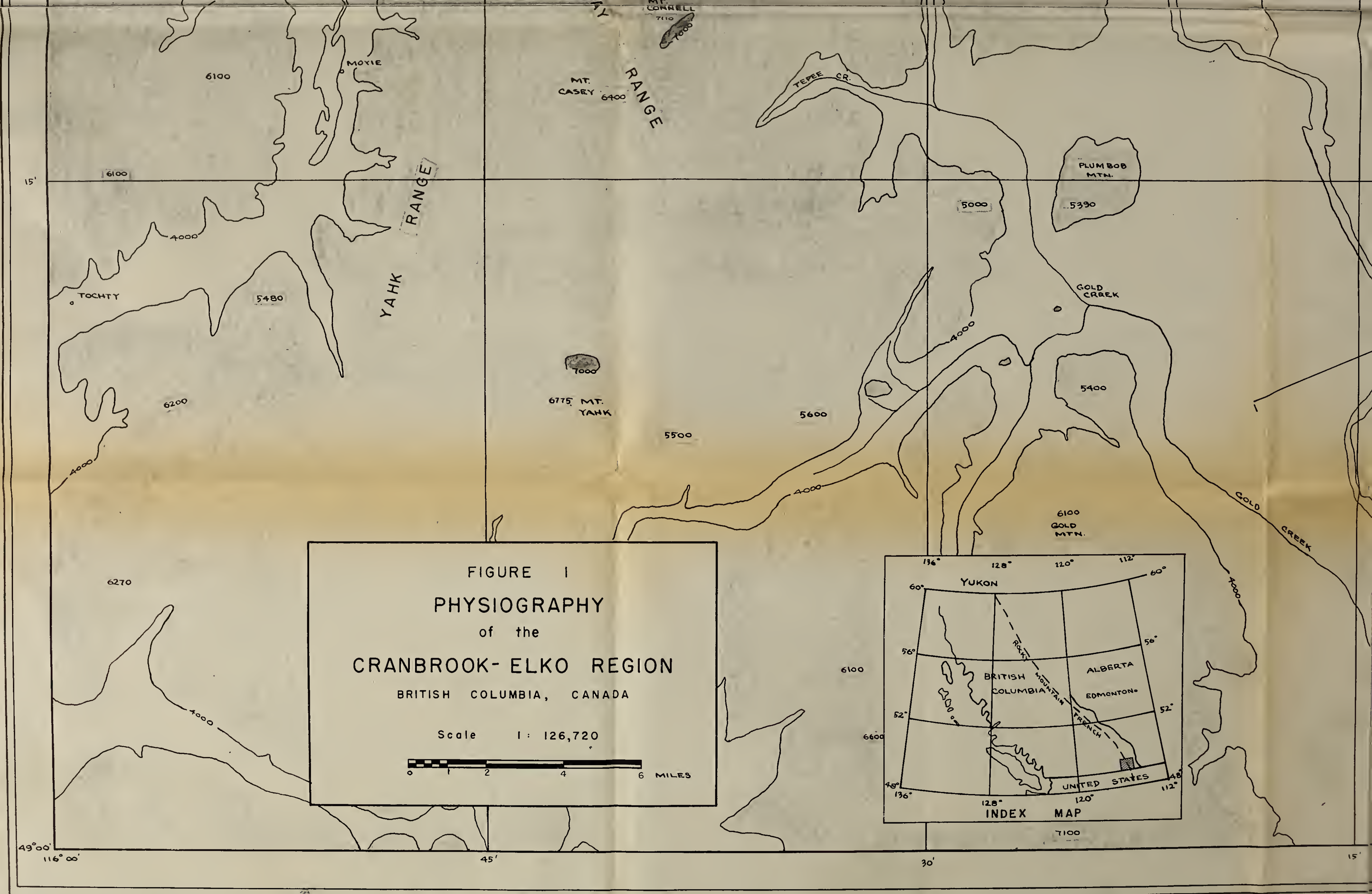
Scale = 1: 16,800. AASL. 11,300'


116° 00'
45'
30'
15'
49° 45'
30'
6100
SULLIVAN HILL
4000
KIMBERLEY
4200
MARYSVILLE
WYCLIFFE
5600
ST. MARY RIVER
ST. EUGENE MISSION
JOSEPH CREEK
EAGER
K
4600
CRANBROOK
KOOTENAY RIVER
A
LAKIT MTN.
8000
WILDHORSE RIVER
LONE PEAK 5910
FORT STEELE
MAUSE CREEK
VERTICAL MTN. 7656
HUGHES RANGE
9100
7900
8200
7500
8400
GALBRAITH CR.
TANGLEFOOT CREEK
MT. FISHER
9300
6000
BULL RIVER
F
7000
DIBBLE CREEK
THE STEEPLES
9000
IRON CR.
8500
E
RAMPART
FENWICK
B
7300
MAYHOOK
JOSEPH CR.
BULL RIVER
4500
DOUGLASS L.
SAND LAKE
7300 MT. BAKER
4800
MT. CRANBROOK 6700
L

30'
15'
115° 00'
49° 45'
30'
HUGHES RANGE
MT. FISHER
GALBRAITH CR.
TANGLEFOOT CREEK
SULPHUR CR.
BULL RIVER
DIBBLE CREEK
THE STEEPLES
IRON CR.
MT. HOSMER
FERNIE
LIZARD RANGE
BULL RIVER
DOUGLASS L.
SAND LAKE
MORRISSEY
B
H
9100
8000
7900
7500
8200
8400
9300
6000
4000
6600
8700
7000
8350
9000
8500
7500
7300
4500

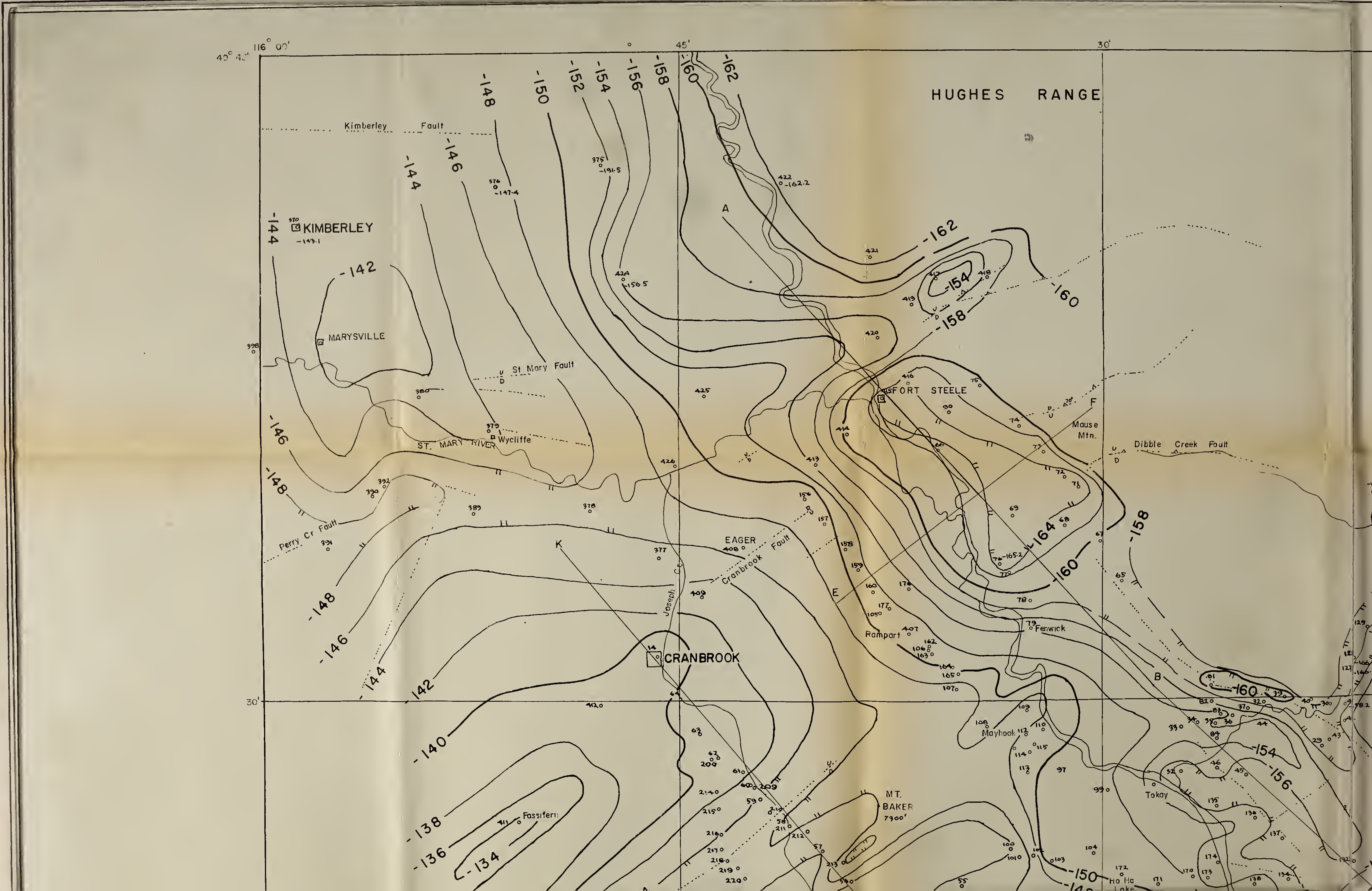
30'
15'
MAYHOOK
BULL RIVER
DOUGLASS L.
SAND LAKE
4500
7300
JOSEPH CR.
4000
7300
MT. BAKER
4800
4500
4000
WARDNER
MT. CRANBROOK
6700
PEAVINE CR.
6600
7000
CONNELL CR.
MT. JOSEPH
7000 7073
4000
JAFFRAY
COLVALLI
5600
6500
MOYIE LAKE
4000
Mc GILLIVRAY RANGE
GOLD CREEK
5300
SAND CREEK
4000
MT. CONNELL
7110
7000
6100
MOYIE
MT. CASEY 6400
TEPEE CR.
6100
RANGE
PLUM BOB MTN.
5000
5390

30'
LIZARD
RANGE
BULL RIVER
4500
DOUGLASS L.
SAND LAKE
H
4000
WARDNER
MORRISSEY
4000
JAFFRAY
C
COLVALLI
G
5600
GALLOWAY
GOLD CREEK
SAND CREEK
7400
6500
5300
4000
SUZANNE LAKE
BROADWOOD MTN.
ELKO
4100
.5500
3000
3800
PLUMBOB MTN.
SHEEP
15'
5000
5390
BAYNES
RIVER



MT. CONNELL
7110
7000
MOYIE
6100
MT. CASEY
6400
RANGE
TEPEE CR.
15'
6100
YAHK RANGE
4000
PLUM BOB MTN.
5390
5000
TOCHTY
5480
YAHK
GOLD CREEK
4000
5400
7000
6200
6775 MT. YAHK
5600
5500
4000
4000
6100
GOLD MTN.
GOLD CREEK
6270
4000
4000
6100
6600
7100
49°00'
116° 00'
45'
30'
15'
FIGURE 1
PHYSIOGRAPHY
of the
CRANBROOK- ELKO REGION
BRITISH COLUMBIA, CANADA
Scale 1 : 126,720
0 1 2 4 6 MILES
136° 128° 120° 112°
60° 60°
YUKON
56° 56°
BRITISH COLUMBIA
ALBERTA
EDMONTON
ROCKY MOUNTAIN TRENCH
52° 52°
48° 48°
UNITED STATES
136° 128° 120° 112°
INDEX MAP

COLVALLI
G
GALLOWAY
5600
5300
SAND CREEK
SUZANNE LAKE
7400
6500
4000
ELKO
BROADWOOD MTN.
4100
5500
7750
7000
PLUMBOB MTN.
5390
5000
3000
3800
SHEEP MOUNTAIN
BAYNES LAKE
WIGWAM RIVER
15'
J
GOLD CREEK
4000
WALDO
ELK RIVER
5400
I
GALTON RANGE
GRASMERE VALLEY
3000
3000
6100
GOLD MTN.
GOLD CREEK
KOOTENAY RIVER
GRASMERE
4000
D
3000
4000
7100
30'
15'
49°00'
115°00'
136°
128°
120°
112°
60°
YUKON
56°
BRITISH COLUMBIA
ALBERTA
EDMONTON
ROCKY MOUNTAIN TRENCH
52°
UNITED STATES
48°
112°
128°
120°
INDEX MAP



116° 00'
45'
30'
HUGHES RANGE
Kimberley Fault
KIMBERLEY
MARYSVILLE
St Mary Fault
ST. MARY RIVER
Wycliffe
Perry Cr Fault
FORT STEELE
Mause Mtn.
Dibble Creek Fault
EAGER
Cranbrook Fault
Joseph Cr
CRANBROOK
Rampart
Fenwick
Mayhook
MT. BAKER 7300'
Fassifern
Tokay
Ho Ha Lake

30'
15'
115°00'
49°45'
HUGHES RANGE
FORT STEELE
Mause Mtn.
Dibble Creek Fault
BULL RIVER
Lime Cr.
Iron Cr.
Fenwick
Mayhook
Tokay
MT BAKER
FERNIE
ELK RIVER
30'

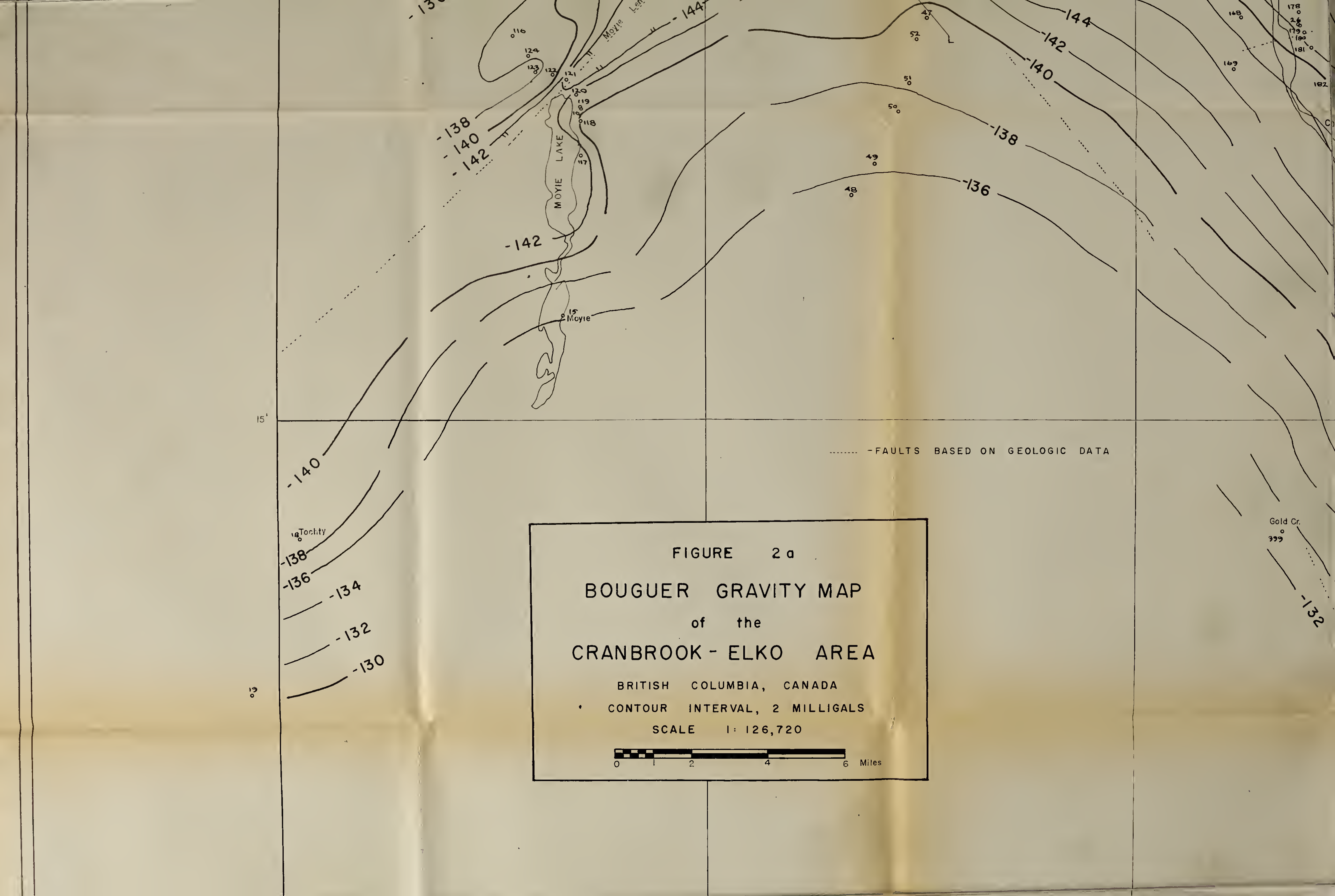


FIGURE 2a

BOUGUER GRAVITY MAP

of the

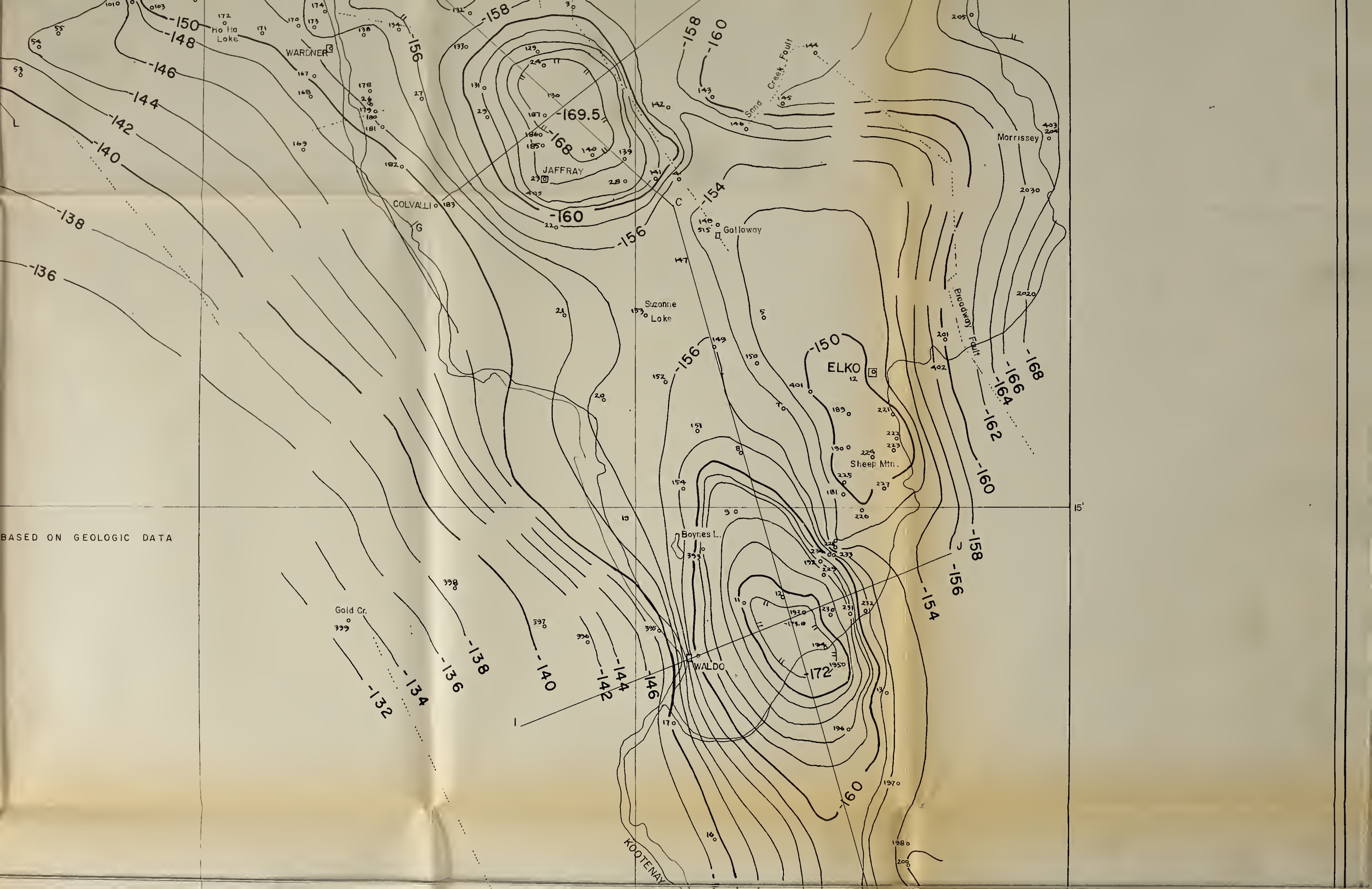
CRANBROOK - ELKO AREA

BRITISH COLUMBIA, CANADA

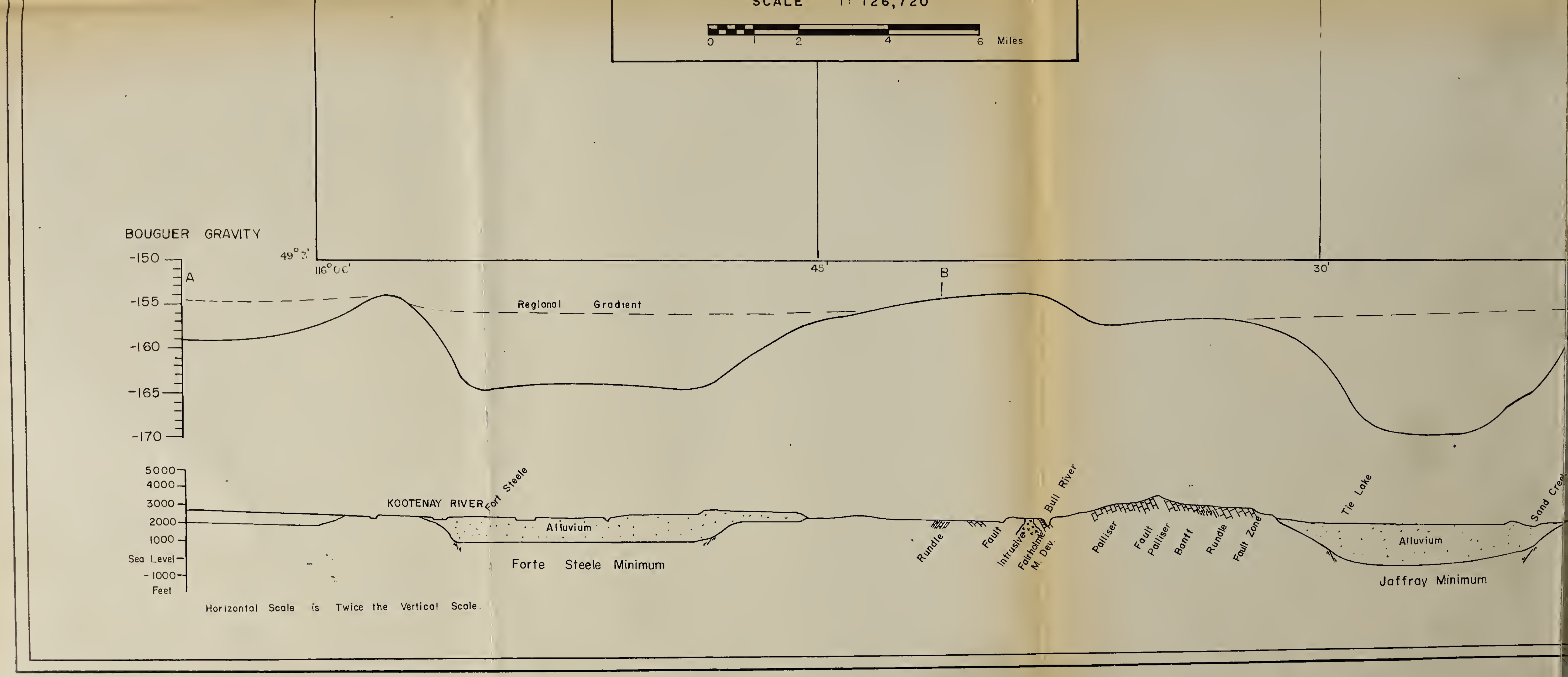
CONTOUR INTERVAL, 2 MILLIGALS

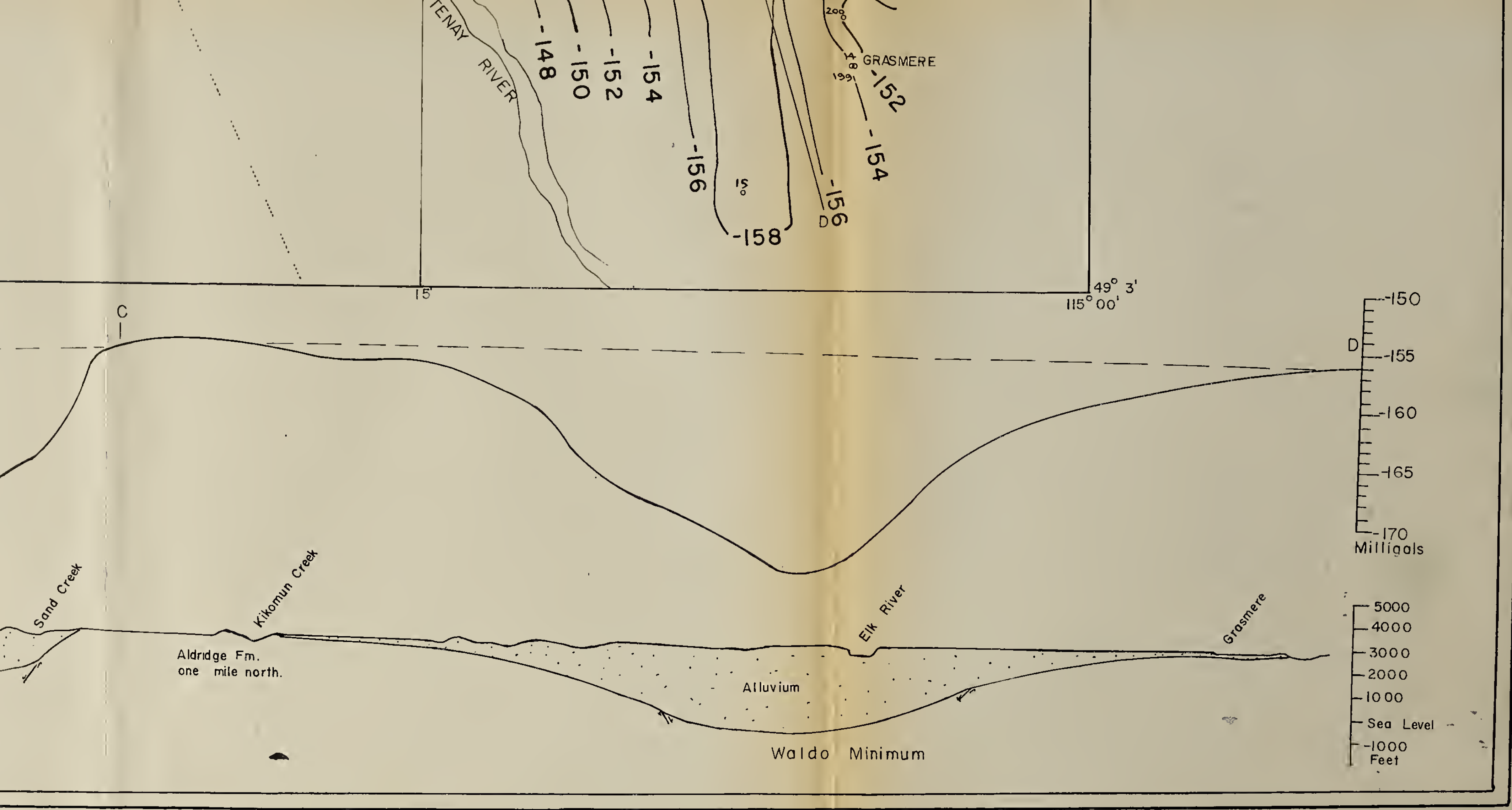
SCALE 1: 126,720

0 1 2 4 6 Miles



BASED ON GEOLOGIC DATA
Ho Ha Loke
WARDNER
JAFFRAY
COLVALLI
Galloway
Sand Creek Fault
Morrissey
Suzanne Loke
ELKO
Sheep Mtn.
Broadway Fault
Boynes L.
WALDO
Gold Cr.
KOOTENAY
-169.5
-172
15'


SCALE 1:126,720
0 1 2 4 6 Miles
BOUGUER GRAVITY
-150
-155
-160
-165
-170
A
49° 3'
116° 00'
45'
B
30'
Regional Gradient
5000
4000
3000
2000
1000
Sea Level
- 1000
Feet
KOOTENAY RIVER
Fort Steele
Alluvium
Forte Steele Minimum
Rundle
Fault
Intrusive
Fairholme M. Dev.
Bull River
Palliser
Fault
Palliser
Banff
Rundle
Fault Zone
Tie Lake
Alluvium
Jaffray Minimum
Sand Creek
Horizontal Scale is Twice the Vertical Scale.



TENAY RIVER
-148
-150
-152
-154
-156
-158
-156
-154
-152
GRASMERE
D
15'
49° 3'
115° 00'
C
D
-150
-155
-160
-165
-170
Milligals
Sand Creek
Kikomun Creek
Aldridge Fm.
one mile north.
Alluvium
Elk River
Grasmere
Waldo Minimum
5000
4000
3000
2000
1000
Sea Level
-1000
Feet